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LIST OF MAPS.

The following Maps will be found in a folder at the end of the Memoir. Numbers I to XIV are original Maps prepared for the Survey Memoir of the present Expedition :—

MAP.	
A.	General Map of the Antarctic Continent.
I.	General Map of Australian Sector of the Antarctic Continent (East Antarctica).
II.	Ross Barrier, Northern Edge. (Inset Cape Crozier.)
III.	Ross Island to the Pole.
IV.	The McMurdo Sound Region.
V.	West Coast of Ross Island. (Inset Erebus Summit.)
VI.	Granite Harbour Region.
VII.	Ferrar-Koettlitz Region.
VIII.	Cape Evans and Inaccessible Island.
IX.	Cape Royds District.
X.	Hut Point Peninsula.
XI.	Glacier Tongue, Ross Island. (Erebus Bay Ice-Tongue.)
XII.	Mackay Ice-Tongue, Granite Harbour.
XIII.	Robertson Bay.
XIV.	Terra Nova Bay.

FOREWORD.

In presenting the following memoir based upon the Glaciology of the Victoria Land sector of the Antarctic Continent, the writers feel that an apology is necessary for the delay in its publication and for its many shortcomings.

The work has, however, been carried out under great difficulties. Hardly had it been commenced when the Great War broke out. Both the writers had to relinquish all extra-European interests for, in the one case five, and in the other six, years. To this obstacle to quick and thorough work must be added the fact that, since the conclusion of the war, the memoir has had to be completed in the moments left free from post-war avocations pursued in different places. The frequent consultations necessary for perfect collaboration have not been possible. Only at considerable personal inconvenience has the minimum co-operation essential for a joint publication been achieved. Such conditions have necessarily caused much delay, and the result is also reflected in the quality of the matter produced.

The form of the book, as expressed in the arrangement of its contents, is perhaps unusual in a memoir purporting to be the direct result of the observations of a single expedition. It was, however, adopted after considerable thought, and the authors still believe it to be the best possible in the circumstances, and bearing in mind the need for economy. The desirability of discussing the *causes* of the phenomena observed has always been borne in mind, and, so far as possible, detailed descriptions of particular ice formations have been avoided.

A natural sequence for the study of all snow and ice forms has been sought. Stages in the changes from freshly precipitated snow, or from water, and the ice formations themselves, have been discussed with particular reference to Antarctic examples met during the particular expeditions on which one or other of the writers have served. The creation of fresh definitions has been avoided so far as possible, but an attempt to formulate a genetic classification of Land-Ice formations, capable of application to all stages of the glacial cycle in all countries, has been considered essential to clear thought. The adoption and repetition of certain definitions of Sea-Ice types, formulated elsewhere by J. M. Wordie after discussion with the writers, has seemed desirable as a further step toward the standardisation of the very vexed nomenclature of this subject.

It is the desire of the authors to point out at the commencement of the memoir that the observations and deductions it contains are not based upon the study of one small region of the Antarctic Continent. In the course of two Antarctic Expeditions

each has gained a thorough knowledge of the ice conditions within the Ross Island-Ferrar Glacier-Minna Bluff triangle, the best known district of East Antarctica, where ice formations of almost all types are represented, some of them in a very specialised environment. In addition, one or other of the writers has visited regions so far apart and so diverse as the Beardmore Glacier region, the Terra Nova Bay region, the Robertson Bay region, and the eastern extremity of King Edward VII land.* In addition, we have had the good fortune to enjoy the friendship and utilise the observations of those members of the expeditions who have penetrated beyond the ice divide of the Great Plateau. Much information has also been obtained and freely used from previously published memoirs of other expeditions, to the authors of which our acknowledgment is made from time to time in the text of this volume.

Finally, all would not be said if we failed to acknowledge the great debt due from us to our late leader, Captain Scott. Never in the history of Polar exploration can the scientists of an expedition have drawn their inspiration from, or owed the opportunity for their work to, a leader whose insight into pure science made him so well able to appreciate the results of their researches. Never can there have been a leader who has personally contributed so much towards the scientific results made possible by his own energy and efforts in geographical discovery.

The calibre of the southern party of Scott's last Expedition was proved when, beside their bodies, was found the treasured bag of geological specimens they had refused to jettison when all went wrong with them and hopes of ultimate safety disappeared. So, right to the end, amongst the intimate thoughts recorded in their journals, may be found many gems of information—shrewd observations made even at the point of death—on every branch of science which fell within their range of observation. Glaciology, as every other science, owes a great debt to Scott and his comrades. It might have owed a greater debt, but for the limitations of those of us who have survived to write up the records.

From the inception of the Expedition, Captain Scott was impressed with the importance of Glaciology. He, himself, had made considered attempts to explain the origin, mode of alimentation and prehistory of such great ice formations as the Ross Barrier and the many masses of Shelf-Ice towards whose accurate charting he had done so much. To his insistence on these points was due the appointment of a physicist to serve as glaciologist to the Expedition.† It was he, again, who insisted upon the inclusion in the northern party of a member who had had some previous experience, both from the practical and from the scientific point of view, of Antarctic ice.‡ In the many discussions which took place at Winter Quarters at Cape Evans, his contributions were always of scientific importance. He was, it is believed, the first man to put forward the theory—since accepted by many eminent glaciologists—that the recent partial deglacierisation of the Antarctic Continent has been due to decreased

* See general map of East Antarctica in the folder at the end of the memoir (Map I).

† C. S. Wright.

‡ R. E. Priestley.

temperature, with consequent diminution of precipitation in the continental region about the Pole. His own writings are full of accurate descriptions and lucid explanations of glaciological phenomena.

No more fitting tribute could be paid to the memory of Captain Scott than an adequate presentation to the public of the observations in the collection of which he played so large a part. Truly a monument more enduring than brass.

While we hasten to acknowledge the debt we owe to the scientists of the Expedition (and also to many who never claimed the name of scientist), for the observations they have recorded and the help they have given, it is fitting that we should also record our thanks to those exponents of the art of photography to whom we owe the illustrations that add to the value of the memoir. Ponting's beautiful illustrations are of world-wide fame. Perhaps even more valuable from the scientist's point of view are the faithful reproductions of glaciological features which we owe to less eminent photographers, among whom G. M. Levick and F. Debenham stand out pre-eminent. To those artists, and to others whose photographs have been less freely used, our thanks are due. Against the individual photographs have been recorded the names of the men who took them.

The memoir is strictly a joint work with equal contributions from the two authors, one of whom has been trained as a geologist and the other as a physicist. It is hoped that the value of the work will be enhanced by this combination, to which circumstance the unusual form of the report is in some measure due. With the exception of isolated paragraphs, Chapters I to IV, VIII and the second half of Chapter XIII have been written by one of us (C. S. W.); Chapters V, VII, IX to XII and the first part of Chapter XIII by the other (R. E. P.). Those portions of Chapter VII dealing with Continental-Ice, Island-Ice, Highland-Ice and Shelf-Ice are the work of the former; the sections on Piedmont-Ice, Confluent-Ice and Ice-Tongues, of the latter. As can be clearly seen, the notebooks of both have been drawn upon impartially throughout. As one of the authors is writing up the Physiography of the Robertson Bay and Terra Nova Bay regions, examples have been mainly chosen from these two areas, in order to make quite certain that overlapping is reduced to a minimum. In all cases where explanations of phenomena are given both the writers are in agreement.

There remains the question of the future. No one could realise more clearly than the authors that the last word has not been said on Antarctic Glaciology. The present economic state of the civilised world is likely for some time seriously to hinder geographical and scientific exploration on a large scale. Nevertheless, before generalisations can be drawn from Antarctic glaciological facts and applied to the climatic history of the earth, extended observations over a large number of years and over a greater range of territory are required.

The variability of the seasons and of the local environment at Antarctic stations is such that most of our observations are open to the criticism that their legitimate application will be restricted to a comparatively small range, both as regards time and place. If geographical activity continues throughout the rest of the present century as in the first twenty years, the end of that period should see mankind in a position to draw the appropriate deductions from Antarctic observations, and to apply them with some certainty of success both to Antarctic prehistory and to the elucidation of the palæo-climatology of the world in general. Not only so, but Antarctic Glaciology must go hand in hand with Antarctic Meteorology in clearing up the weather problems of the southern hemisphere and, indeed, of the greater part of the world. It is foolish to hope to be able to forecast the weather of Australia, South America and South Africa, if the effect of the great reservoir of cold about the South Pole is ignored, or only partially understood. Associated with this great reservoir of cold, controlled undoubtedly in great degree by the sheet of Continental-Ice which caps it, flow the winds which dominate the air circulation of a large portion of the globe.

To lovers of Polar exploration and devotees of Polar science, there is one thing above all others which should give comfort and hope for the future. Without flourish of trumpets, indeed, to exert its greatest effect, with far too little advertisement, there has been born at Cambridge, through the far-sighted policy of the Trustees of the Scott Memorial Fund, the *Polar Research Institute.* Properly exploited and properly served, this institute—already in being—will prove a nucleus to which should gravitate all that is best in past, present and future Polar work. As a repository of records, as a centre of research, as an inspiration to future scientists and explorers who direct their attention to the "ends of the earth," it should prove indeed invaluable. The original MS. and photographs, diaries, notebooks and other records used in compiling the present memoir will be deposited there under the care of the Director. It is hoped that this precedent will be followed by all workers in this particular branch of science. Should this be so, the work of discovery within the Arctic and Antarctic Circles—still the least known regions of the earth—should proceed apace, and the researches of the future be no longer handicapped, as too often they have been in the past, by the absence of continuity of record.

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July, 1922.

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CHAPTER I.

SNOW AND ITS DERIVATIVES.

Meterological Data.

Before proceeding to a discussion of the occurrence and supply of snow on the Antarctic Continent, it is necessary to review in some detail the meteorological data bearing on this subject, so far as they are known. The data in question will be found in the Meteorological Reports of the present expedition, where they are given in full. Only those conclusions which seem to be of chief importance will be briefly reviewed in the present memoir.

(1) Vertical Distribution of Temperature in the Atmosphere.

Our knowledge of the temperature gradient in the atmosphere is derived from meteorological observations during balloon flights, and from the readings of special self-recording thermographs attached to small balloons released from various meteorological stations. In Table I is set down the generalised result of observations made in temperate latitudes.

Table I.—Mean fall of temperature, with height at successive levels, in degrees centigrade per kilometre.

0–1 km.	5·3° C.	Mean 5·2° C.
1–2	4·8° C.	
2–3	4·8° C.	
3–4	6·0° C.	
4–5	6·3° C.	Mean 6·6° C.
5–6	6·6° C.	
6–7	7·0° C.	
7–8	6·6° C.	
8–9	6·8° C.	
9–10	5·3° C.	
10–11	3·5° C.	
11–12	0·1° C.	
12–13	0·2° C.	
13–14	0·3° C.	
Mean 0–9 km.	6·1° C.	

It will be seen that, up to a height of 4 km., the average decrease in temperature per 100 metres is about 0·52° C. At this point an increase in gradient to about 0·66° C.

per 100 metres sets in, and at about 8 km. the maximum temperature gradient occurs. Above this height, the temperature gradient rapidly decreases until the isothermal layer is reached at a height between 11 and 12 km. Here the gradient becomes zero, or may even be reversed in sign.

These facts are explained by Gold* in the following manner. At all points below the isothermal layer, radiation from the air exceeds absorption in it, and the deficiency in energy is such as can be made up by convection from the earth's surface and by condensation of water vapour. This deficiency (radiation minus absorption) becomes less with greater altitudes and finally, in the isothermal layer, a position is found where radiation and absorption are equal and convection currents cease to become operative.

In his paper, Gold further notes that the height of the isothermal layer will be greater the greater the absorbing power of the atmosphere for terrestrial radiation. This is important to us, in that it seems clear that the Antarctic air, with its low temperature and consequent small content of water vapour, might have a small coefficient of absorption; and one might, therefore, expect to find the isothermal layer in the Antarctic at a significantly lower level than in lower latitudes. Such observations as have been made point to the same conclusion, since it is known that over the Equator the isothermal layer lies at a height of 17 km., and, in our own latitude (50° N.), at a height of 11–12 km. Observations at Kiruna (67° 50′ N.)† give a height of 9·8 km. for the lower limit of the isothermal layer, and the inference therefore is, that the latter may become progressively lower as either Pole is approached.

Unfortunately the isothermal layer was never reached by any of the balloons sent up by Dr. Simpson from our winter quarters at Cape Evans, the highest recovered record being from a height between 6 and 7 km., on December 25th, 1911.

It seems to be well established, however, that the summer temperature gradient up to this height is practically the same as that observed in temperate regions. This fact, considered in conjunction with Gold's prediction that there is a limiting value to the temperature of the isothermal layer (a value which from known data may be calculated as − 80° C.), leads us once more to the tentative conclusion that the isothermal layer in the Antarctic may be at a comparatively low altitude.

The observations made by Dr. Simpson show‡, as stated above, that the summer temperature gradient at Cape Evans is nearly the same as that observed in lower latitudes, the mean of all the summer balloon ascents giving the following results :—

(1) A mean gradient of 0·68° C. per 100 metres up to 2500 metres.
(2) Above this, a reduced gradient of 0·54° C. per 100 metres ; followed by
(3) An increase in gradient.

During calm weather in the winter, a temperature inversion is always observed in the lowest layers close to the ground, or snow surface. This is due to cooling of the air layers in contact with the surface by radiation.

* 'Proc. Roy. Soc.,' A, vol. 82, 1909.

† Maurice, C.R., 156, March 13, p. 738.

‡ 'Meteorology,' vol. 1, p. 41 *et seq.*

Any blizzard or sufficiently strong wind sweeps away this surface layer and causes a thorough mixing of the surface air and the superincumbent layers, with consequent rise of temperature, establishing by this means a gradient similar to that existing in the summer months. As soon as the wind ceases in the winter months, a fresh layer of cold air at once commences to form at the surface through radiation, only to be swept away in its turn by the next blizzard.

From the evidence which has been brought forward by Simpson, it is, however, clear that the large temperature difference which exists in the winter months between the Barrier and the Ross Sea must decrease with increasing height, and there is every reason to believe that, at a height of 4000 metres, this difference of temperature will be very small or non-existent.

In the summer months a cold layer cannot form, owing to solar radiation falling on the surface and to the convection currents caused in the atmosphere by the rise of the heated air. Even during the winter it seems impossible that there should be an inverted temperature gradient in the surface layer over open sea, owing to the comparatively high temperature of the sea and the thorough mixing caused by convection currents.

(2) Surface Temperature.

From the above it will be clear that the surface temperatures must be largely dependent on the radiation received by and emitted from the earth, and that the altitude of the sun is the chief determining factor in summer. A factor of very great importance, however, is the physical condition of the surface which is absorbing and radiating energy. So much is this so that a change in the physical properties of this surface will involve a change in the observed surface temperature. A surface of low thermal conductivity and low specific heat will be very effective in raising the temperature of the air in contact with it while it is receiving energy from the sun, and equally effective in cooling the air by radiation when the sun is below the horizon. A covering of loose powdery snow will thus cause greater variations in surface air temperature for a given change in solar energy than will a sheet of water or of solid ice.

This is indeed found to be the case, the variations in air temperature on the Ross Barrier during the day being two to three times as great as the corresponding variations at Cape Evans. The daily variation of temperature on the Barrier is, in fact, comparable with that observed near the Equator, notwithstanding the relatively small daily variation in insolation in these high latitudes.

It is important to note that the maximum temperature on the Barrier on a clear summer day is little less than that observed at Cape Evans, while the minimum temperature is far less. Similarly, there is little difference in the mean temperature of these two regions during the summer months, while the Barrier has much the lower mean temperature during the winter.

There is no reason to doubt, however, that if the sea were frozen over and the sea-ice covered with a sufficient thickness of light dry snow, the temperature

range during the day over McMurdo Sound would be practically the same as that on the Barrier. The high specific heat and high thermal conductivity of bare sea-ice and sea-water thus operate in preventing large variations of temperature.

It is possible, also, that the decreased specific heat of ice at low temperatures* may play some part in increasing the temperature range, particularly on the Antarctic Plateau.

Further evidence of the close relation between solar radiation and mean temperature on the Barrier is given by the fact that the curve of annual temperature lags only eight days behind that representing the variation of received solar energy.

These facts unite to raise a suspicion that the atmosphere in the Antarctic may be more transparent for heat radiation than the atmosphere in lower latitudes.

(3) Radiation and Absorption.

The solar constant (" S ") is defined as the number of calories received per minute by a square centimetre surface placed perpendicular to the sun's rays at the boundary of the atmosphere when the earth is at its mean distance from the sun. This constant has been evaluated by many observers, notably by Abbott and Fowle,† and the value may be taken as approximately 1·922 calories per minute. The inherent difficulty in the experimental evaluation lies in the fact that the coefficient of absorption of the sun's rays by the atmosphere is not known, and indeed almost certainly varies, not only from day to day, but also from hour to hour.

The mean value of " S " on the earth's surface lies not far from one calorie per square centimetre per minute, and is dependent on the thickness of air traversed, to some extent on the humidity of the air, and on the amount of CO_2 in the atmosphere. The energy absorbed in transmission is approximately proportional to the total mass of each constituent of the atmosphere. Oxygen and nitrogen absorb very little, and there is reason to believe that molecular scattering is sufficient to account completely for the loss of solar radiation at levels above that of Mount Wilson, say, 6000 ft.,‡ except in the ultra-violet region, where there is considerable absorption due to ozone § in the upper atmosphere.

It is clear that the total amount of the " dust " (which absorbs the longer wave-lengths at low levels in low latitudes)|| and the water vapour may be small in the Antarctic. It is, therefore, reasonable to suppose that absorption of the sun's radiation by these factors is likely to be less marked in the Antarctic than, say, at the Equator. Observations of the percentage content of CO_2 in high southern latitudes are almost entirely lacking, the exception being occasional measurements during the French Expedition of 1908, when Gourdon found that the CO_2 content at winter

* *See* Appendix, page 476.

† 'Astrophys. Journ.,' XXXIII, April, 1911.

‡ L. V. King, 'Trans. Roy. Soc.,' A, vol. 212, p. 429.

§ Rayleigh, 'Nature,' July 8, 1920.

|| L. V. King, *loc. cit.*

quarters was only 2·05 per 1000, compared with 2·56 at Cape Horn, and 2·82 in Europe.*

We might, therefore, expect a larger proportion of the available sun's radiation to reach the surface in Polar regions than in Europe, for instance, were it not for the obliquity of the sun's rays in these high latitudes. In Table II is shown the relative total radiation received at different latitudes, on the assumption that the atmosphere transmits the whole of the radiation from the sun.

TABLE II.

Latitude.	Thermal Days.	Latitude.	Thermal Days.
0°	365·2	50	249·7
10°	360·2	60	207·8
20°	345·2	70	173·0
30°	321·0	80	156·6
40°	288·5	90	151·6

This Table represents the total amount of radiation which would fall during the whole year on a square centimetre surface placed perpendicular to the sun if there were no atmosphere. The numbers there given, therefore, require modification, in order to take into account the effect of the greater absorption by the atmosphere, due to the low altitude of the sun in high latitudes and the consequent greater thickness of air traversed.

King† has drawn the curves reproduced in Fig. 1 to show the variation in the incident total radiation with the sun's altitude. These are calculated from data obtained at Mount Wilson in the United States, and it will be seen that, at very low solar altitudes, the "sky radiation" on a horizontal plane is more intense than that from the sun itself.

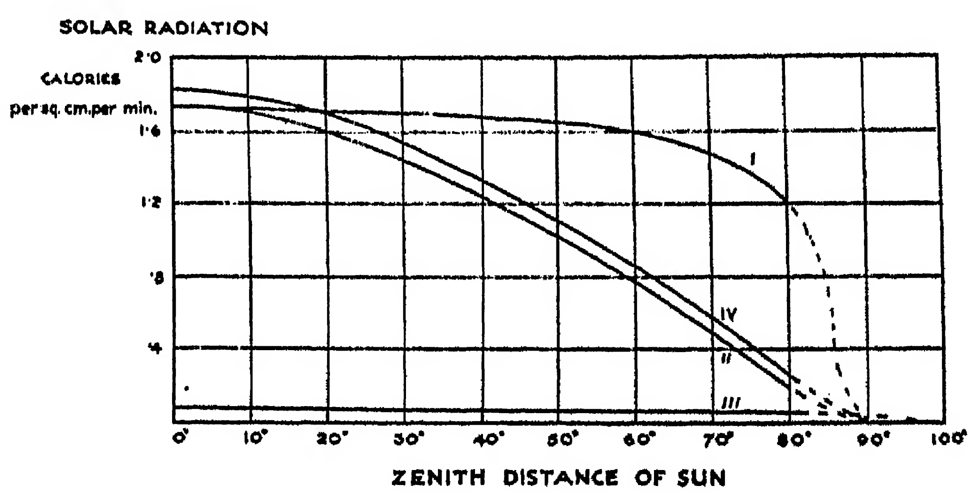


Fig. 1.

Curve I.—Total intensity of solar radiation per sq. cm. per min. normal to the sun's rays.
Curve II.—Total intensity of solar radiation per sq. cm. per min. on a horizontal plane.
Curve III.—Total intensity per sq. cm. per min. for radiation from the sky on a horizontal plane.
Curve IV.—Total radiation of sun and sky per sq. cm. per min. on a horizontal plane.

From Table II the total yearly insolation on a square centimetre perpendicular to the sun's rays at Lat. 80° S. is seen to be only 43 per cent. of the available quantity

* 'Expedition Antarctique Française, 1903–5,' 'Glaciology, 1908.'

† *Loc. cit.*

at the Equator; and from a consideration of the curves in Fig. 1, it is clear that the actual quantity incident on a level square centimetre surface will be considerably smaller.

Systematic observations of the intensity of radiation in Antarctic regions seem to be quite lacking, but we may gain some idea of the magnitude of the effect from a consideration of isolated observations.

(a) *Observations with solar radiation black bulb thermometers.*—In the 'Discovery Meteorological Report' (p. 469) we find the data shown in Table III:—

TABLE III.

Date.	Temperature in Degrees Fahrenheit.	
	Large Black Bulb Thermometer. (average maxima).	Air Temperature.
1902—	°	°
September	40	−12·0
October	69	− 8·5
November	103	−12·0
December	123	23·1
1903—		
January	120	26·1
February	97	11·2
March	53	0·8

The mean reading of the black bulb thermometer for December, 1902, is seen to be 123° F., corresponding to a mean air temperature of 23·1° F.—a difference of 100° F. On December 21, the absolute maximum of the radiation thermometer was 154° F., corresponding to a mean air temperature of 17·8° F., a difference of 136° F. Such a large difference as this is seldom observed, even near the Equator, where the sun's rays have to traverse only half as much atmosphere at noon as they do at the Discovery Winter Quarters in McMurdo Sound. At mid-day, on December 21, the maximum solar radiation is to be expected (the zenith distance being then about $54\frac{1}{2}$°). Calculation shows that the maximum radiation is then only 58 per cent. of that which would be expected, *cet. par.*, at the Equator when the sun is in the zenith.

(b) Confirmatory evidence of the importance of radiation is furnished by observations of the air temperatures at which ice, lying on black rocks, begins to melt in the sun's rays. The observations are sporadic in character, the most striking effect seen by us being noticed on October 13, 1911, at 4 p.m., melting taking place with an air temperature of 0° F., while the sun had an altitude of only 12°. (The actinometer time*, at this moment, is given as 5 secs).

(c) A further indication of the diathermancy of the atmosphere in the Antarctic is derived from data on certain of the sledge journeys, obtained by means of the photographic device called the actinometer. The type used by the Expedition was the "Watkins' exposure meter," in which the intensity of the light, for photographic

* *See below.*

purposes, is estimated by counting the number of seconds required for a strip of sensitised paper to darken to a certain tint in direct sunlight. At first this little instrument was used only when photographs were to be taken, but later, on the main southern journey, a regular routine was observed, and the actinometer time was taken as a measure of the amount of radiation (of wave-length capable of affecting the photographic paper), reaching the earth's surface at different times. The results showed that the actinometer time given at noon, on the Barrier, is, at times, little greater than that obtained with the same instrument on the clearest days in a climate such as that of California. The numbers obtained on the Barrier were lower than those observed on sledge journeys in the neighbourhood of the Western Mountains, and about one-half those observed on the clearest summer days in England.

An interesting single observation with the actinometer leads one to suppose that the intensity of radiation of these wave-lengths on the plateau, 9000 feet above sea-level, is but little greater than that received under similar conditions on the Barrier, though a smaller amount of air and water vapour has here to be traversed by the sun's rays. This conclusion, though based on very slender evidence, is worthy of mention, as bearing on the view that the air in the Antarctic, which contains so little moisture, may transmit a very large proportion of the radiation from the sun.

This suggestion, that the Antarctic atmosphere is particularly transparent to the sun's rays, seems to be in direct contradiction to the results of L. V. King,* that scattering in the atmosphere is able to account for the observed absorption. King's results, however, apply to conditions above the level of Mount Wilson, where the atmosphere is free from dust, and to the shorter wave-lengths. Though the maximum of the energy wave-length curve, as measured on the earth, does lie in the visible range, it does not seem impossible that water vapour and ozone may exert a significant influence in absorbing energy emitted by the sun, though their absorption bands lie in the infra-red and ultra-violet. It is, however, certainly difficult to see how the absorption of the ultra-violet radiation could be less in the Antarctic than elsewhere.

As mentioned previously, a factor of greater importance than the total incident radiation, when we are considering the absorption of the radiation by the surface on which it falls, is the physical condition of the surface upon which the radiation falls—that is, its specific heat and its coefficients of absorption and of reflection. It is clear, for instance, that radiation falling on a black rock surface is very strongly absorbed, and that the surface of the rock will be considerably heated. On the other hand, a large part of the radiation which falls upon a white snow surface is reflected back into space, the snow surface being thus less heated.

On bright sunny days during the Antarctic summer, areas of exposed rock of quite small extent were commonly heated so strongly by the sun, that the vertical convection currents set up in the atmosphere above them caused the formation of dense cumulus clouds at an elevation of about 1000 feet. (Plates I and II.) Excellent examples of such areas which may be cited are the peninsulas of Cape Royds and Cape Barne. These,

* *Loc. cit.*

situated as they are within a few miles of Cape Evans, were constantly under observation during the summers of 1910–11, 1911–12 and 1912–13. Such cumulus clouds are also commonly seen over water holes in a sheet of Fast-Ice. The occurrence of these local cumulus clouds in the Antarctic over rock masses is undoubtedly due, not only to the powerful radiation, but also to the fact that the sun's altitude is always so low that the clouds thus formed over such small areas are not of sufficient extent to shade them.

Absorption of Long Wave Radiation.

When considering the absorption of radiation from the sun in our atmosphere, it was stated that the maximum of the sun's energy curve lay in the visible spectrum. This is not true of the radiation from the earth, the energy maximum of which, on the contrary, lies in the infra-red. For radiation from the earth, the infra-red absorption bands of water vapour are clearly of predominant importance; though absorption by CO_2 exists at wave-lengths close to 15μ, it seems doubtful if its importance is great. On the other hand, ozone also has an absorption band very close to the wave-length where the energy curve for the earth's radiation is a maximum. Clearly then, the joint effect of these three is of much greater importance in absorbing the earth's radiation than the radiation from the sun, so that a poverty of water vapour, CO_2, or ozone, in the earth's atmosphere would probably have a notable effect in lowering the surface temperature during the Antarctic winter months, particularly in view of the small heat conductivity and specific heat of a loosely compacted snow surface, such as exists on the Ross Barrier or on the Polar plateau.

(4) The Main Antarctic Circulation.

The meteorological observations of all the expeditions which have worked in the Ross Sea quadrant, together with those of Drygalski, Bruce, and Nordenskjöld, show that the general drift of the air at sea-level, on the edge of the continent, is south-easterly—that is, the wind blows in general from some point in the S.E. quadrant.

By far the greater portion of the air displacement takes place from this quarter, and the south-easterly gales frequently blow with great force for several days on end. The most reasonable explanation is, that these gales are caused by a glacial anti-cyclone which dominates the continental circulation—the air flowing outwards radially from the great Antarctic plateau.

Above each anticyclone a cyclone forms, on account of the relatively rapid vertical temperature change caused by the cold dense air. These cyclones convey air from higher latitudes to the Antarctic Continent, and supply the air which passes outwards near the surface.* It is important to note, however, that nowhere does the Antarctic Continent pierce through the anticyclone.

Such a main system of circulation, if uncomplicated by other forces, might be expected to give rise to a series of winds blowing from nearly due south. The easterly component, which is superimposed upon this simple system, may be attributed to the effect of the rotation of the earth.

* 'Report on Meteorology,' vol. I.

The one other sheet of Continental-Ice* on the surface of the earth is to be found in Greenland, and here the work of Nansen, Peary and others has proved the lower air circulation to be similar to that just described as occurring in the Antarctic. The cooled air flows radially off the elevated dome of the ice capping, the direction of the winds coinciding roughly with the line of greatest slope.

Objections to Hobbs' view†, that a glacial anticyclone lies everywhere above the Continent, have been raised, on the grounds that an anticyclonic pressure distribution demands an excess of evaporation over precipitation; whereas it is known that immense masses of ice are yearly discharged into the sea in the form of icebergs, so that precipitation must, in fact, exceed evaporation.

As pointed out by Dr. Simpson‡, precipitation of snow can take place on the surface in the manner postulated by Hobbs, and there seems no doubt that precipitation of this type does occur in the Antarctic. The amount is, however, small, and greater snowfalls would occur if air close to the ground were, in any manner, forced to move faster than that in front of it. Such an action would cause the air behind to rise and precipitate a portion of its moisture in the form of snow. As will be seen later, the pressure distribution accompanying blizzards provides the mechanism for such a movement. It must be emphasised, however, that the factor predisposing to snowfall which operates most strongly in winter is powerful radiation from the snow surfaces.

There can be little doubt that, at least in winter, the chief formation of snow takes place in the early portion of blizzards, except in the case of coastal regions near the open sea. Dr. Simpson has, in his Report, given a full exposition of the cause of the blizzard winds in McMurdo Sound, but it seems desirable to restate the main circumstances, in view of their importance to the Glaciology of the Antarctic.

As already stated, there is a large temperature difference near the earth's surface between the Ross Sea and the Barrier, which is most strongly developed during the winter as a result of radiation and the formation of a temperature inversion over the Barrier. This temperature gradient, combined with the rotation of the earth, causes a southerly wind with a pronounced easterly component. On account of the obstacle formed by the high ranges of South Victoria Land, there is a concentration of the moving air into the McMurdo Sound area,§ causing winds of extreme violence in this region, and causing at the same time an increased pressure difference between McMurdo Sound and the Barrier. It frequently happens that the cold layer formed near the surface at first allows the faster moving layers of air to slide over it, the blizzard only extending down to the earth's surface when this protecting layer has been swept away.||

* *See* Chapter V on "Classification of Land-Ice Formations."

† Meinhardus, '*Deutsche Sudpolar Expedition.*'

‡ 'Meteorology,' vol. I, p. 268.

§ Map IV.

|| The best proof of this was afforded by the fact that the arrival of a blizzard at Cape Evans or Cape Royds was frequently heralded by the sweeping past of clouds of snow and drift (at blizzard speed) at a height of two or three thousand feet above sea-level. This would sometimes continue for many hours before the blizzard descended to the level of the station.

The occurrence of blizzards is associated with the travel of waves of pressure across the Plateau, Barrier and McMurdo Sound, these waves possibly originating at a point in about 80° S. lat. and 120° W. long., moving from the south-east, and reaching Cape Adare and Cape Evans eighteen and nine hours respectively after reaching Framheim, the headquarters of Amundsen's Expedition. These waves modify the normal pressure gradient, often intensifying it and thus causing blizzards in such districts as McMurdo Sound and Robertson Bay.

The normal distribution of wind velocities is anticyclonic, the most frequent weather being a calm; but superposed upon this anticyclonic distribution at Cape Evans are the strong winds caused by the pressure wave intensifying the normal pressure distribution, the predominant factor being the difference in temperature between the air over the Ross Sea and over the Barrier. This difference is greatest in winter, and is due to intense radiation from the Barrier surface.

As pointed out by Dr. Simpson, when a pressure wave travels across the country with a speed of 30 miles per hour it sets up its pressure gradient faster than the air can get into motion. In these conditions the air behind moves faster than that in front, causing the former to rise, and under appropriate conditions precipitate moisture in the form of snow. Precipitation may, however, also occur as a result of the forced mixing during blizzards of the cold surface layer and the air above, the air stream being in this case in turbulent motion.

Hobbs* has recently re-stated the problem of the glacial anticyclone, following the remarks of Dr. Simpson in the Meteorological Memoir of the Scott Expedition. The general weather conditions associated by Hobbs with a glacial anticyclone cannot be gainsaid, though we cannot agree with him in his explanation of the cause of its inception. Thus, Hobbs states that the dome-shaped glacier of considerable extent is a necessary condition for the formation of the glacial anticyclone; the heavier air cooled by contact with the surface flowing (if we ignore an easterly component due to the earth's rotation) down the line of greatest slope. This causes a vacuum above the central area of the mass, and air is here drawn down from above.

One or two facts remain to be explained :—

(1) Why is the air flowing uphill in the region of the Pole ?

(2) Why does the action continue in summer, when the snow surface should be warmer than the air in contact with it (at least in clear weather) ?

(3) How is the central area nourished, in view of the fact that air is here descending ?

As regards these queries, we believe that the flow of air uphill is the *cause* of the greater snowfall in the polar area and of the misty and foggy conditions near the Pole, though no doubt this action is complicated by the inequalities of the surface. The conditions over the central boss are, in our opinion, desert conditions such as are found in other anticyclonic areas; but we believe precipitation does (very slightly) exceed ablation on the elevated plateau.

* 'Proc. Am. Phil. Soc.,' vol. lx, No. 1, 1921, p. 24.

As regards the continuance of the glacial anticyclone in summer, we would suggest that the dome-shaped surface may be the result, rather than the cause, of the glacial anticyclone. We would, in fact, prefer to place the origin of the anticyclonic conditions at the boundary between snow-covered continent and either open water, water with ice-covering, or bare rock surface. At such a line of demarcation a horizontal temperature gradient must exist.

If this can be granted, as seems reasonable, the prime cause of the anticyclone is associated with the difference between the physical properties of a snow surface and the adjacent rock or water surface, one contributing factor being the high reflectivity of the former. The descent of air in the centre is a natural consequence. One has then only to assume that precipitation less ablation is a plus factor at the centre of the continent, and that this factor decreases towards the periphery of the ice-mass, and the dome-shaped surface follows as a natural consequence. This would be an expected result of the ablative action of a wind which increases in velocity as the edge of the Continental-Ice is approached.

In these conditions, the descending air will probably be warmer than the ice surface and may deposit snow on contact. The cooled air will then flow generally downhill, as in the manner postulated by Hobbs.

The essential difference between our view and that of Hobbs is, that a dome-shaped shield of Continental-Ice can, given a favourable climatic environment, arise on any large glacierised* land-mass, irrespective of the original contour of the ice surface. The glacial anticyclone is, therefore, not dependent upon a pre-existing dome surface, but upon the horizontal temperature gradient around the boundary of the glacierised region. *The dome-shaped contour is a result, and not a cause.*

It follows, from the view expressed above, that, just as the initiation of a blizzard is due to a horizontal temperature gradient (in the case of Antarctica between continent and sea), so cessation of wind will not take place until this temperature gradient has been greatly reduced, or reversed.

The fact that the wind was found to blow uphill near the South Pole is difficult of explanation on Hobbs' theory, but seems to present less difficulty on our view. We may, in fact, look on this phase as a visible attempt of the circulation to complete the dome-shaped surface and to shift the highest point of the continent to a more central situation. This is in conformity with our suggestion that the dome-shaped surface is the result, not the cause, of the glacial anticyclone.

(5) Local Wind Circulation.

As might be expected, local variations in wind direction, or even a local reversal in direction, will occur in particular localities, and, in point of fact, practically every sledge party has brought back evidence in some form of the extremely local character of the winds.

* The term "glacierised" is used in this memoir to indicate a land covered with ice and snow in contrast to a "glaciated" land, which implies a land sculptured by ice.

From numerous journeys up the glaciers cutting through the South Victoria Land horst, we have learnt that, in the glacier valleys, the wind blows down the valley almost continuously, though rare occasions are known when it has blown in the reverse direction. The same phenomenon has been noted in Robertson Bay opposite the various glaciers. On the journey down the coast of Victoria Land, from Evans Cove to Cape Evans, in October, 1912, the Northern Party recorded, opposite the mouth of every transverse valley of the mountain range which borders the coast, sastrugi whose direction testified to the presence of normal down-valley winds.

The members of the Expedition who took part in the winter journey to Cape Crozier have recorded that, on all occasions when they reached the junction between the low sea-ice and the higher Barrier cliff, " the cold air streamed off it " (the Barrier). As, in the winter, the Barrier surface may be some 20° or 30° F. colder than the sea-ice, this is not at all surprising. A good example of local wind circulation was constantly noted in the vicinity of the winter quarters at Cape Evans. During journeys in the spring over the 15 miles of sea-ice intervening between Cape Evans and Hut Point, the wind often changed in direction or force during the journey. On days when it was calm at Hut Point and Cape Evans, there was often a 15 or 20-mile wind blowing from the S.E., about midway between the two points, in the vicinity of Glacier Tongue.

On such occasions, it was observed that Glacier Tongue appeared to be the dividing line between the two distinctive areas, and this circumstance was also observed and recorded by members of the first Shackleton Expedition.* It is, in fact, considered that the Tongue itself may owe its present shape partly to excessive precipitation near the boundary between these two areas. This point is dealt with more fully in Chapter VI, under the sectional heading " Ice Tongues."

The best example of the local character of the wind, however, was observed in the second winter on October 1. On this occasion a blizzard had been raging for a short time with a very thick and heavy drift. After a few hours, the wind velocity gradually decreased, until the recording instrument registered a dead calm. In itself this was sufficiently surprising to cause remark, but a further cause for surprise was observed on leaving the hut. Less than half a mile away, between Cape Evans and Inaccessible Island, and only a little to the S.W. of the Cape, a blizzard still raged. Heavy drift to a height of at least 200 feet blotted out the slopes of Inaccessible Island, and the roar of the gale came to us distinctly, resembling the continuous noise of a heavy surf on a sandy coast. The line of demarcation between the blizzard and the calm area appeared to be very sharply drawn, but doubts as to the stability of the sea-ice prevented closer investigation. To the north-east of the hut, a sight but little less remarkable was to be seen. Only 300 yards away in this direction a whole procession of small " willy-wa's," or wind eddies, moved slowly from N.W., to S.E. carrying with them a small quantity of snow, which might either have been picked up from the ground or have been formed in the vortex of the miniature whirlwind. Further off in the same direction, a slight breeze of about 15 miles an hour blew from the N.W.

* Sledging Diary, R. E. Priestley.

Cape Evans, therefore, was included in a calm belt little more than ¾ mile wide, sandwiched between a mild breeze from the N.W. and a typical blizzard from the S.E., which carried drift to a height of not less than 200 feet. No snow was falling at the time. Almost exactly similar cases were recorded on several occasions at Cape Adare.

During the laying of the depôts in January and February, 1911, parties were frequently travelling on the Barrier within quite a short distance of one another, and, on several occasions, these parties reported totally different weather conditions. On more than one such occasion, a comparison of diaries has shown that one party has been held up by a blizzard while another only 20 or 30 miles away was favoured by comparatively fine weather, and this occurred although both units were travelling on a practically level plain at a distance of at least 50 miles from the nearest land.

Another example of a different type was recorded on the return journey of Dr. Atkinson's supporting party on the main polar journey. Here, at the junction of the Beardmore Glacier and the Barrier, and at a distance of about 4 miles from the glacier, we could see a couple of miles to the east a swirling line of drift carried by a strong S.S.E. wind apparently coming down the main glacier outlet. A couple of hundred feet above us was that portion of the blizzard which issued from the "Gateway,"* so that the roar of the wind could be loudly heard. This blizzard overhead was also evidently carrying a great deal of drift, but none of it reached the Barrier level, while we ourselves experienced only a light 15-mile breeze from the S.S.E.

Convincing evidence of local variations in the direction of the stronger Antarctic winds is best furnished by the sastrugi on snow surfaces. These sastrugi, which will later be described in detail, are the irregularities on a snow surface which has been exposed to wind, either during the deposition of the snow covering or after. Sastrugi, though laid down or cut out in many different forms, show in every case, with a considerable approach to accuracy, the direction from which the wind blew at the time of their formation. The direction of orientation of the sastrugi is here taken as the mean wind direction without further proof, but from all the data collected at Cape Evans, and at the Gauss Winter Quarters, and from the experiences of numerous sledging parties, it appears likely that this is reliable to a quite remarkable extent. In fact, next to their violence and duration, one of the most remarkable properties of the blizzard is the extreme steadiness of the mean wind direction, combined often with unsteadiness of force. In those regions where the sastrugi are "mixed," *i.e.*, two or more series cutting at different angles are present, they give equally decisive evidence of the prevalence of an equal number of directions from which the prevailing winds of these particular districts may be expected to blow.

Good examples of such areas of "mixed" sastrugi may be seen on the tracts of sea-ice opposite either side of any main outlet valley of the Victoria Land mountain range (Fig. 2). Thus, opposite the centre of the mouth of the Ferrar Glacier Valley, and close to the coast, there occur sastrugi which betray the predominance of a westerly wind

* Map III.

blowing down the valley. As one marches along parallel with the coast in either direction from this central position, areas are reached where the sastrugi from these plateau winds are intermixed with another series, which proclaims the activity of the south-easterly gales common to this portion of the Antarctic coast. A similar area of " mixed " sastrugi is met if one walks directly away from the glacier valley, and, in all three of these transition regions, sastrugi of indefinite shape exist, in addition to those already mentioned. These last may be attributed to a coincidence in time of the south-easterly gales along the coast with the westerly gales down the valley, a coincidence which may result in the neutralisa-

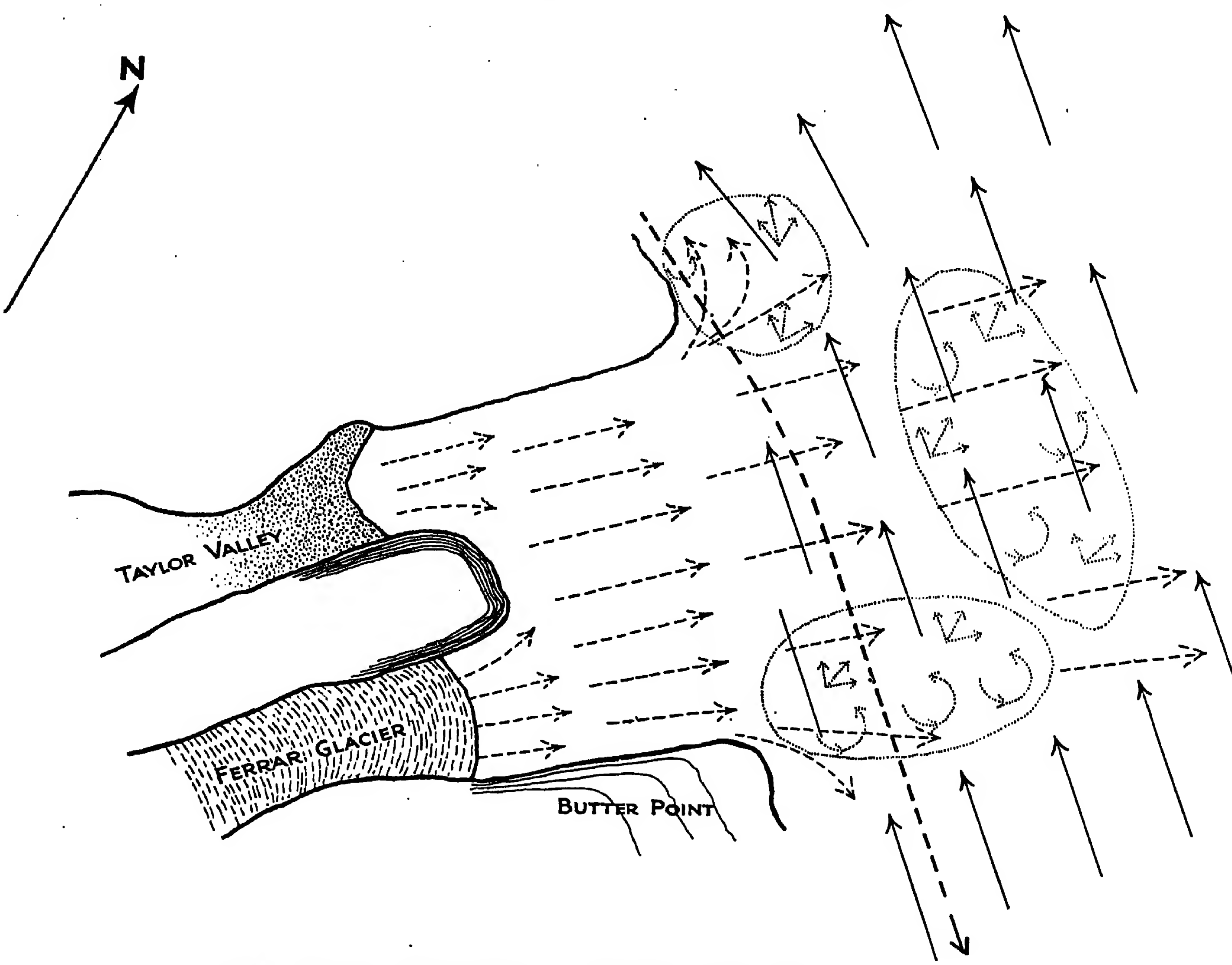


Fig. 2.—Sketch of New Harbour. Areas of " mixed sastrugi " shown ....

tion of both, and which suggests that both types of wind belong to the same system. Thus, we have in these mixed areas sastrugi with a S.E.–N.W. trend, sastrugi with approximately a W.–E. trend, and also a third set which have no particular direction of prolongation, but look as if they have been dropped from the clouds.

The orientation of the sastrugi during the outward journey towards the pole and the return of the party under Dr. Atkinson are shown in Map III. The first point of interest is the remarkable correspondence between the directions plotted from the record taken on the outward and inward journeys on the stretch from Corner Camp to the foot of the Beardmore. Secondly, in $80\frac{1}{2}$–$81\frac{1}{2}°$ south, a region is con-

spicuous where the sastrugi were markedly "mixed" in character. There was every evidence, in fact, to show that in this region the winds were very variable in direction. Here also the sastrugi were much less pronounced, so that this area (from 80½–81½° south lat. in 170° east long.) may fairly be considered an area of light variable winds, which appears to be also an area of excessive precipitation. Another area of mixed sastrugi on the Barrier route is seen on the stretch from Hut Point to Corner Camp; but this differs from the former area, in that here the predominating set of sastrugi is well defined from the south, but is overlaid with less marked sastrugi from other directions—west through south to east. Further to the north, in the bay bordered by the slopes of Mount Terror, a region distinguished by calms and heavy precipitation is characterised by deep drifts of soft snow which make travelling very difficult.

If we compare this evidence with the weather conditions that have been noted on the Barrier journeys, we find that the stretch from Hut Point to Corner Camp is swept by an unusually high proportion of blizzard winds; and it appears also to be an area of comparatively heavy precipitation with much overcast weather and bad light. Heavy winds also predominate along the stretch from Corner Camp to Bluff Depôt, and these winds, which are accompanied with relatively little precipitation, are the direct cause of the hard surface and strongly marked sastrugi which characterise this region. From One Ton Depôt southwards, on the other hand, less heavy wind and more overcast weather is correlated with a softer surface and less well-defined sastrugi, until between 80½–81½° south lat. the sky usually remains overcast, and the accompanying distinctive effects are bad light, light winds, fairly continuous light snowfall, and comparatively soft surface. Beyond this region, again, an increase in mean wind force is reflected upon the surface, the sastrugi becoming more pronounced and pointing definitely from the south-east, while the surface becomes progressively harder and better for sledging.

It must here be pointed out, that the circumstance that the sastrugi show definite directions does not imply that the light winds also blow from the directions shown, but merely indicates the trend of the heavy gales. In fact, during one day on the outward journey in lat. 83° S., on December 3, 1911, we were favoured by a fairly strong wind (with snow) from the N.N.W. quadrant. This is the single case we have noted on the Barrier of a breeze of over 25 miles per hour from any direction with a northerly component. The occurrence of this wind was evidently related to the disastrous blizzard which held the party up at the foot of the Beardmore Glacier.

From Map III. it will be seen that the sastrugi run parallel to the general trend of the coastline, except in the vicinity of One Ton Depôt, where the Skelton and Mulock Inlets appear to direct the air immediately down from the plateau.

On the journey up the Beardmore Glacier the winds blew in general down the glacier from the polar plateau.*

Another strip of the Antarctic coastline of considerable extent was traversed by the Northern Party in their journey from Inexpressible Island to Cape Evans, in October

* The southward-bound party and Dr. Atkinson's party on their return journey experienced no strong winds on this stretch.

and November, 1912. During the whole of this journey of some 200 miles, notes were made of the prevalent direction of the winds, both as displayed by the meteorological conditions at the time of traverse of the region and as deduced from the sastrugi which covered the sea-ice over which the party was travelling. The prevalent

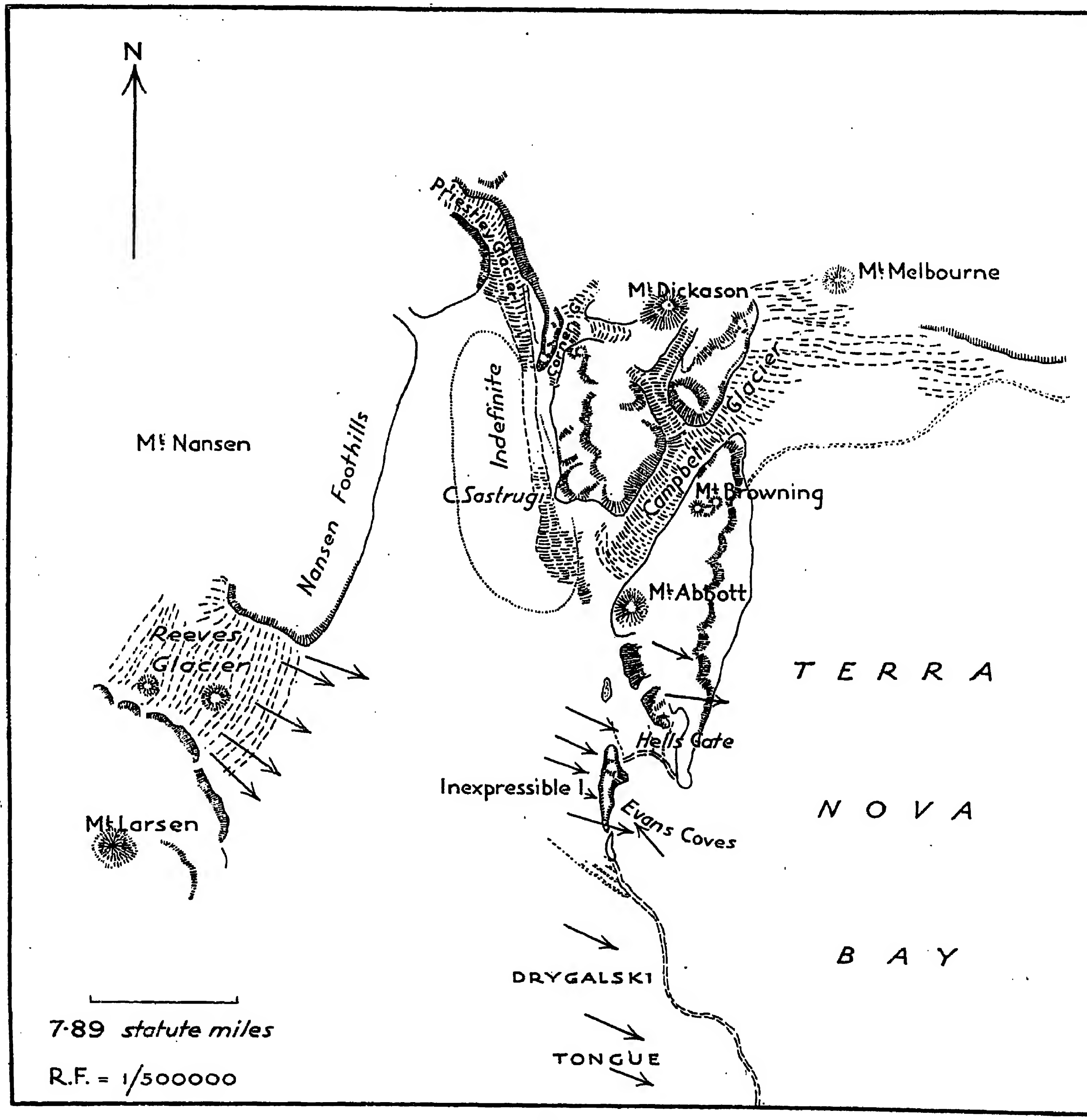


Fig. 4.

strong wind in the neighbourhood of Inexpressible Island during the previous autumn, winter and spring had been from slightly west of north-west, and it was obviously controlled in its direction by the valley to the south of Mount Nansen down which it swept (Fig. 4). This wind and similar down-draughts from other glacier valleys continued to hold sway almost uninterruptedly until some 20 or 30 miles south of Evans

Coves. It was not until some way past the summit of the Drygalski Ice Tongue that confused sastrugi were met, which suggested that another wind of the same order of strength was beginning to take effect. As the party marched on towards the south these sastrugi became more definite in direction, until at least three sets could be made out quite certainly, and it then became evident that they were due, respectively, to the Reeves Valley wind already mentioned, to a draught blowing down the David Glacier, and to the main south-easterly gales of the Ross Sea area which here blew parallel to the coast as S.S.E. winds.

Before the south side of the Ice Tongue had been reached, the suppression of the westerly sastrugi had become almost complete, and the south-easter once more held complete control of the local snow sculpture.

From here right down to McMurdo Sound the sastrugi showed the influence of a predominating southerly wind, the influence of which was only complicated in two ways. The first type of exception was observed opposite each valley which transected the mountain range, and which thus, as in the case of the Nansen Valley, gave egress to the cold plateau down-draught. In such cases the south-easterly sastrugi would be more or less completely obliterated, the thoroughness of the work being directly dependent on the size and maturity of the valley. Had this strip of coast been deeply dissected, westerly winds might have been the rule rather than the exception; but, as it was, the south-easterly stream was only slightly ruffled by these westerly counter-currents. The second exception to the general rule was demonstrated by the occurrence of comparatively calm areas, such as that already described as occurring on the Barrier south of One Ton Depôt. Prominence is given in the meteorological reports of the Northern Party to a similar but much more marked calm area on the west side of Robertson Bay (Fig. 5). It seems certain that when the position of these areas and their relation to the surrounding country is finally worked out, it will be found that they will be closely correlated with those more immaturely dissected portions of the coastline which are also so favourably situated as to be in the lee of some prominent projection of the coast, and thus are sheltered from the winds blowing parallel to the latter.

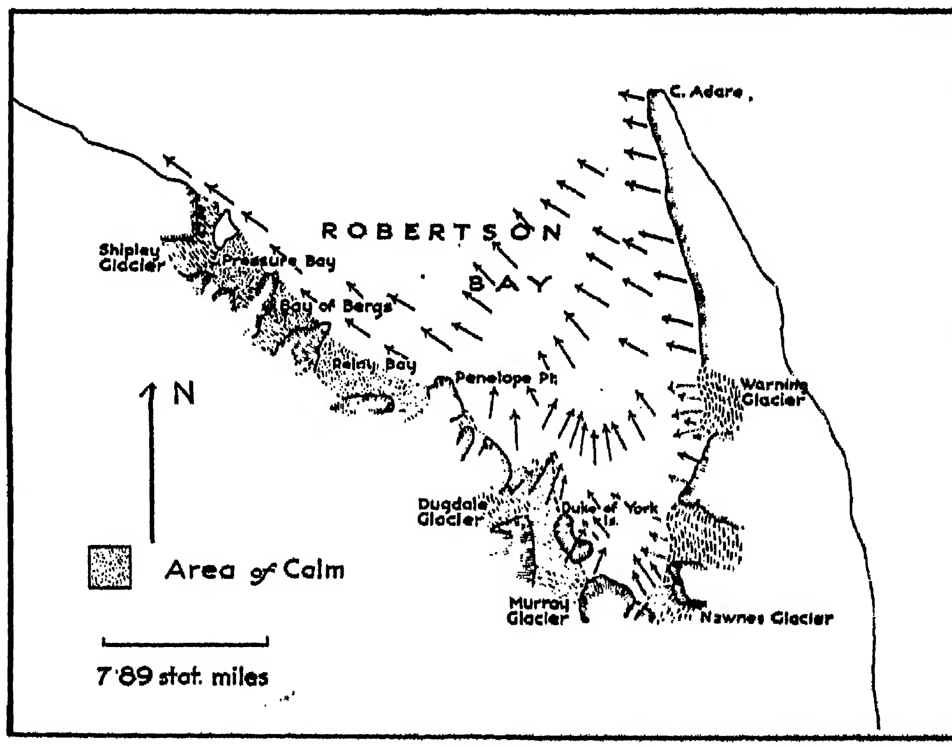


Fig. 5.

The sastrugi met on this sledge journey have been plotted, together with those further south and those in the Robertson Bay district, and it is evident that similar conditions govern the weather along the whole of this long stretch of the Antarctic mainland.

It is safe to conclude, therefore, that the lower wind circulation, though governed by the position and shape of the great polar plateau, may be modified or even reversed by the local conditions. It seems certain, indeed, that the high temperatures experienced during the blizzards at Cape Evans can hardly be ascribed to winds blowing from the cold Barrier, but must be put down to mixing of the air in the lower strata in the immediate vicinity of the station.

If the inception of the blizzard corresponds to the time at which the high south-easterly wind above finally extends down to the surface, it will be clear that the blizzard is likely to commence at different times in positions quite close to one another. Thus, the blizzard at Cape Evans from July 7 to July 13, 1911, did not commence on the Barrier to the south of Ross Island until July 10. Prior to the commencement of the blizzard on the Barrier, the period July 5–July 9 was one of calm at this place, the temperature being very low (— 72·9° F.) on the 6th and rising gradually from the 7th to the 9th, after the blizzard had commenced at Cape Evans. It is therefore difficult to escape the conclusion that the air at Cape Evans during the first portion of the blizzard descended to the surface in the immediate vicinity of the station.

PRECIPITATION.

Great difficulty has always been experienced in distinguishing between winds of blizzard force carrying drift only, and those in which snow is being freshly formed. This difficulty arises from the fact that in the former the drift may extend to a height of certainly 200, and probably many hundred, feet, so that, even with a clear sky above, no signs of the sun can be seen. It is probable, in fact, that 30 feet of heavy drift is more than sufficient to obscure the sun.

When the Northern Party were encamped at the Hell's Gate moraine in February, 1912, they were harassed by strong drift-bearing winds for many days together. On one such day, when the sun was completely hidden by the drift and there was only the merest suggestion of a faint glow in the quarter where he was, it was found, on climbing up the side of one of the moraine cones, that the drift was only 20 feet high. In its lower layers the drift was so thick that it was impossible to see the tent from two or three yards away. Similar, but less striking, examples were observed in McMurdo Sound.

During strong blizzards with drift it is usually impossible to say whether snow is falling at the time or not, though it seems likely from other considerations that blizzards with high air temperatures are synchronous with a true snowfall. It was frequently noted that although a significant deposition quite often appeared to take place during the earlier half of the blizzard, all fresh snow was usually removed, or very nearly removed, during the second half. Indeed, the net result of a gale would frequently be

one of erosion rather than deposition. Striking evidence of this was afforded by the fact that footmarks made in the newly-drifted snow in the first few hours of a gale were commonly seen to stand up above the general level by as much as a foot when the wind had finally died away—a result which is, of course, to be attributed to the "packing" of the snow under the pressure of the weight of the man or animal that had made them (Plate XXV).

Another notable example of the erosive action of a blizzard occurred on July 27, 1912, at Cape Evans. The gale in question had been preceded by one on July 25, which had left behind it a significant deposit of snow in the vicinity of the hut. This fresh drift had covered the wooden door* of the magnetic cave to a depth of 3 feet, yet the second gale not only removed the fresh drift, but undermined the door of the cave and carried it bodily out to sea.

Examples of this denuding type of blizzard might be multiplied indefinitely, but perhaps none more striking occurred within our experience than that of the ten days' gale in May, 1911, at Cape Adare. For at least six days out of the ten during which it raged this gale was free from snow, and, at its close, there was scarcely a vestige of snow left on the beach on which the station was built. All along the edge of the cliff of Cape Adare the drifts which had been thought permanent had been removed and everywhere fresh screes of coarse gravel were exposed, while the snowdrifts which had been several feet thick on the ice-foot at the close of the third day of the wind had disappeared entirely long before the wind dropped.†

This same gale also displayed very well the drastic effect of a change of direction during the course of a gale. Four days before it dropped, it swung from E.S.E. to S.S.E., and within two days it had completely removed the drifts it had itself caused to form behind prominent obstacles. It brought very little snow from this new quarter to replace that which had been removed, and the only deposit it left behind was a large quantity of spray-ice.

Thus, an unknown proportion of the Antarctic precipitation is masked by the presence of detrital snow borne by the wind in which the snowfall is taking place. If one were compelled to judge entirely from such situations as are exposed to the continual outrush of Barrier drift, it would be almost impossible to detect with certainty the formation of fresh snow in heavy winds. The few exceptions are those when snow has been observed to fall as what has been termed "fluff-ball" snow, a type of snow which consists of many tiny spicules or needles aggregated together, the whole aggregation being often no larger than a pin's head. This type of snow is, at Cape Evans, usually associated with high winter temperatures, and has been observed several times in blizzards at Cape Adare. We have thus so far been unable to obtain any near estimate of the relative proportion of drift and falling snow in an Antarctic blizzard, and evidence enough has already been secured during the last few years'

* The door lay horizontally, giving ingress to the magnetic cave *via* a rough flight of steps cut in the snowdrift.

† 'Antarctic Adventure,' R. E. Priestley.

work to make certain that any estimates of snowfall which leave "blizzard snow" altogether out of consideration cannot pretend to approximate accuracy. There is little doubt that at least a fourth of the snowfall at Cape Adare, during 1911, occurred at periods when winds of gale force were blowing and when it was impossible to measure the amount with any accuracy by the methods at present in use.

Both at Cape Evans and at Cape Adare the initial stages of a blizzard were quite commonly accompanied by a definite snowfall, but usually its later stages were free from falling snow. Not only so, but, as already stated, all, or nearly all, of the snow deposited earlier in the gale was swept away before its termination.

More easily recognised snowfalls may occur during light winds which are not sufficiently powerful to raise snow crystals or fragments of crystals more than 4 or 5 feet. The clearest cases of snowfall, however, occur when there is no wind at all, or only a light air which can scarcely be dignified by the name of wind. In these latter cases the fall of snow is perfectly definite, though usually of very small amount. A slight snowfall of this type with a precipitation of $\frac{1}{4}$ inch or so of snow frequently precedes a blizzard and feeds it with sufficient light material to fill the air with drift to such an extent that one's vision may be limited for hours to a range of about 6 feet.

Snow is formed in the air whenever the latter is cooled until it contains more water-vapour than that required to saturate it at the given temperature. Thus, 1 cubic metre of saturated air at freezing-point contains 4·834 grams of water-vapour, while at $-10°$ C. (14° F.) the maximum amount the same volume of air can hold in the form of vapour is 2·154 grams. If, therefore, air saturated at freezing-point is in some manner cooled to $-10°$ C., approximately 2·7 grams of moisture per cubic metre must be turned into the solid phase as snow or hoar frost. This cooling of 10° C., therefore, will cause the formation of 2·7 grams of snow for every cubic metre cooled, and this snow will fall to the ground if the forces tending to hold it suspended in the air are not too strong. It will be seen by reference to the Appendix that the cooling of the cubic metre of saturated air by a further 10° C. does not liberate a further 2·7 grams but only 1·3 grams, so that the maximum amount of snowfall for a given cooling of the air depends very largely on the original temperature. Obviously, another controlling factor is the percentage humidity of the air if, as is generally the case, it is not already saturated.

The necessary cooling of the air may occur in either of two ways :—

(*a*) By adiabatic expansion of the air.

(*b*) By direct cooling of a mass of air through meeting a colder surface or a colder body of air.

(*a*) *Precipitation by Adiabatic Expansion of Air.*

Under this heading, we may distinguish two different phenomena :—First, a cooling due to a lowering of barometric pressure, and second, a cooling due to expansion of air

which is forced to rise. The cooling experienced in the first case is at best small, for air at freezing-point, for example, is only cooled 2·6° C. by a decrease of 1 inch in the barometric height. This effect will be insignificant, for, even with such an extreme barometric fall, the air can only deposit snow crystals if it is almost at saturation point, and then only in minute quantity.

Considerable amounts of snow can, however, be formed in the Antarctic by the second process, that is through the compulsory ascension of air. In the Antarctic summer, it is quite generally to be noticed that over every small patch of bare rock which is being warmed by the sun, a dense local cumulus cloud hovers at a height of some hundred feet above the rock (Plate I.). To this form of cumulus cloud, the snow-capped mountain with bare slopes on the Beardmore Glacier owes its name of "The Cloudmaker" given to it by Shackleton (Plate II), for usually when the sun is shining a white cumulus cloud hovers just over its top. The height of the cloud here coincides with the top of the mountain. As the air on the rock slopes of such an ice-capped mountain is warmed by the rock, it ascends and part of its moisture condenses when the air has been sufficiently cooled by adiabatic expansion. Were it not for the presence of the snow cap, the top of the mountain might also be warmed sufficiently to cause powerful ascending currents, which would place the cumulus cloud at some altitude above it and prevent any deposition of snow on the top. Such a sequence of events occurs in many places where bare rock expanses have been seen by the present Expedition. One of the characteristics of the isolated cumulus clouds, which owe their origin to the process mentioned above, is that their existence does not appear to be accompanied by a "fall" of snow. It seems probable that they are composed of snow-forms having a high ratio of surface to weight, so that the ascending currents to which they owe their formation are sufficiently powerful to keep the crystals suspended in the air.

Whatever the cause may be, it is clear that under these circumstances a snow deposit usually only takes place at the higher altitudes. Similar effects may, however, be produced by a forced rise of air such as that which is produced by the travel of a pressure wave accompanying a blizzard, and it seems probable that this method of deposition is of considerable importance in the Antarctic.

An interesting case of snow-formation due to adiabatic cooling of air was observed generally in the Antarctic, but was best developed in the vicinity of the Cape Adare Station. Here the hut is sheltered from the S.E. by the steep and precipitous slopes of Cape Adare. During blizzards, therefore, eddies were formed in the wind, and here the drift-free and snow-free air was quite commonly cooled locally to the saturation point, with consequent formation of snow. Though this phenomenon was commonly observed at Cape Adare, it does not appear that any great amount of snow was precipitated. The cloud in the lee of the Cape was of quite a local character, and the snow formed in this manner was gradually drawn into the main current of the wind and was there evaporated. It is, however, by no means certain that such eddies formed to leeward of a glacier wall may not give rise to part of the deposition in the form of

snow cornices, though by far the major part must be caused by direct addition from drift snow carried by the wind.

Situated as they were in the lee of Cape Adare, the Northern party were also able to note the frequent occurrence of " willy-wa's " carrying locally formed snow. During the winter blizzards, the gusts of wind were often of extreme violence, and seemed to partake of the nature of diminutive cyclones travelling across the low-lying beach. These gusts were very sudden, and it was noted that a large number of the small cyclones carried snow in their vortices, though others did not. As the cyclones travelled along the bare wind-swept beach, they could be seen at times suddenly to develop into swirling columns of snow, this precipitation being probably brought about by the cooling of the air by expansion. When struck by one of these whirls, the hut shook as if it had been hit violently by a solid body, and occasionally some of the outer weather-boards would be torn away by the impact of the gust. At those times the mercury in the station barometer would " bump," or vary in height, by as much as $\frac{1}{2}$ inch.

(*b*) *Precipitation by Direct Cooling.*

This method of precipitation may also be considered as arising in either of two different ways :— by cooling of a mass of air through direct contact with a colder solid, or by the mixture of two air-bodies at different temperatures. In both processes, the possibility of precipitation is conditioned by the humidity of the air in relation to the change of temperature experienced. We will consider the two cases separately.

The formation of snow by cooling in contact with colder surfaces is frequently to be seen in the winter at low temperatures and on clear nights. On such occasions, radiation into space is very active from any objects such as ski, ski-sticks, etc., and all such articles left outside the hut speedily become covered with crystals deposited from the almost saturated warmer air about them. The effects of this phenomenon may be distinctly annoying. Thus, considerable difficulty was occasionally experienced in making observations for time with the transit instrument, owing to the deposition of crystals, not only on the body of the telescope, but also on the lenses. The amount of deposition due to such radiation is not, however, large, though it is known that radiation is the cause of the formation of the inverted temperature gradient near the ground in calm weather during the winter. That this action is not confined to the winter months is shown also by the regularity with which ice crystals would form each night during the autumn and spring on the glass sphere of the Sunshine Recorder, putting this instrument out of action until the film had been removed by the observer.

Where this method may be relatively most effective in causing precipitation is on the upper plateau and on the Barrier, where radiation is most effective in the winter. Here the air currents meet the cold surface, and must deposit snow in amount depending on the humidity and temperature of the air, and on the degree of cooling which takes place. While traversing the plateau on the polar journey, Bowers notes in the log

"almost continuous parhelia."* Since parhelia can only be formed by snow crystals, we may confidently state that the formation of snow on this portion of the plateau takes place almost continuously, in the summer months at least, though it is clear from Bowers' notes that he considers the total amount of snowfall to be very small. The reason for this will be seen when we come to consider the effects of the wind on the snow surfaces.

It is no less difficult to evaluate the importance of precipitation due to the mixture of two masses of air at different temperatures. We have given reasons (based partly on the high temperatures usually prevailing during blizzards) for the view that large volumes of air must have descended in the immediate vicinity of the observing stations of the Expedition. Since the high temperature is very often accompanied by a light snowfall, it would seem that the rise in temperature and the fall of snow are probably due to the same cause, *viz.*, the mixture of the cold surface layer of air with the descending air which was originally warmer and has been further warmed by the compression experienced in its descent. The warm air will of course have a low percentage humidity, and the cold air will contain a small amount of water vapour. We believe that a large portion of the total amount of snow formed during blizzards in the dark winter months is due to this cause. As, in any case, the snowfall is almost always succeeded or accompanied by a blizzard which blows much of the loose snow away, it seems impossible to estimate the total effect of the precipitation, the influence of which is wholly masked by the denuding effect of the wind.

As regards the probable amount of snow which is formed in blizzards during which high temperatures prevail, it is important to note that the high temperature during the blizzard demands that the percentage humidity of the air which has sunk from higher levels must usually be low. Also the large and often sudden rise in temperature early in the blizzard suggests that the cold air near the surface prior to the commencement of the blizzard has probably been mixed with a considerable mass of warm air. These conditions are not favourable to snow formation.

It seems probable, indeed, that the wind during blizzards is in turbulent motion (as evidenced by the temperature variations); snow may be formed at one instant at a given spot above the surface, only to evaporate before reaching the ground. In any case, snow is most likely to be formed in a rising current of air which then probably has sufficient upward velocity to prevent deposition, and when the air current bearing this snow is forced towards the earth, conditions at once become favourable to evaporation of the snow. On the whole, there seems every reason to believe that, in normal conditions, the amount of snow formed and deposited by mixing of air layers during

* When the sun is very low, parhelia are associated with a light snowfall, usually in the form of minute crystals not more than one-hundredth of an inch long. These are at times quite invisible to the naked eye, and can only be seen as slowly-falling bright points of light when the observer is facing the sun. The note by Bowers refers to the area close to the Pole, where the wind was blowing uphill, and the formation of parhelia, as pointed out in Chapter VI (Ice Formations Characteristic of an Advanced Stage of the Glacial Cycle), is probably best explained with reference to the forced ascent of air and the rugosities of the surface.

blizzards is unlikely to be of any great amount. This result is doubtless associated in some measure with the high ratio of surface to volume in the types of snowflakes formed under such circumstances. The latter factor operates in the direction of preventing the snow formed in an ascending current of air from falling to the ground and in enabling evaporation to take place more quickly in a descending current.

(c) *Precipitation through Other Agencies.*

Precipitation is known to occur in the Antarctic through other agencies, but these are dependent chiefly on local conditions at the place of observation. Of these might be mentioned first the deposition of spray in the vicinity of the open sea. This is the single instance in which precipitation in the form of water occurs in the regions with which we are dealing. Rain over the land surface is almost unknown to us, the solitary exceptions in the present Expedition being recorded from the station at Cape Adare and at sea off the Ross Barrier. There are two essentials necessary for the formation of spray-ice deposits, *viz*., open water close to the land and on the windward side of it, and winds sufficiently strong to blow the tops from the waves and to carry the water to its place of deposition. At Cape Evans, this method of deposition was not of frequent occurrence, not because of a lack of wind at the spot, but because the sea on the windward side of the Cape was in general ice-covered, except during the month of March and for a few days in February and April. Blizzards at this time of year, however, add notably to the icefoot by the deposition of spray, which freezes immediately it touches the surface. Even at 200 or 300 yards' distance from the coast and at a height of 100 feet, the spray deposited is significant in amount. On the top of the icefoot in these cases, the spray ice always takes the form of ridges inclined at an angle of about 30° from the vertical towards the direction from which the wind blows. They are illustrated in Plates III and IV. These spray ridges may be as much as 2 feet from crest to crest, with hollows between them into which the foot can easily enter, and which may reach a depth of over 20 inches.

It was indeed fortunate that the sea to the south and south-east of Cape Evans was open for only this short period in each year, as the damage caused in blizzards at this time of the year was almost irreparable. This is due to the fact that the salt water is driven by the wind into every conceivable corner. Particularly it enters the meteorological screen with its louvred sides and covers all the instruments. The thermograph appears to be unusually susceptible to the salt water, and much of the trouble it gave in the second winter must be attributed to the rusting of the pivots of the driving-wheels of the clock. To the same cause must be assigned the rapid deterioration and final disintegration of the copper wires which carried the current for operating the lamp in the magnetic ice cave. In this case, the salt hastened the corrosion to such an extent that the wires were soon eaten completely away in places.

This method of deposition will be treated more fully under the heading "Icefoot" (Chapter IX).

Almost exactly analogous to the process just described is a deposition usually accompanied by what is called "Frost Smoke" (Plate V). The formation of frost smoke is dependent upon the presence of a body of open water (over which it is formed and above which it rises to no very great height) at a period of low air temperature. Numerous records of the temperature at which frost smoke was observed to form over the open sea suggest that this phenomenon requires that the air temperature should not be above about 0° F. Another point that seems to be well established is that wind plays a very significant part in its formation, as it was noted that, at low temperatures, frost smoke formed even in very light winds, while, at temperatures of zero F., or a little below, a considerable wind velocity (over 20 miles per hour) was necessary for the formation of the smoke. These two facts would appear to suggest that the formation of frost smoke was conditioned rather by the rate of cooling of the sea surface, or by the temperature gradient above the sea, than by the air temperature alone.

A peculiar form of precipitation occurred quite frequently on the Barrier in the summer, and at Cape Adare. This was caused by the movement of super-saturated air, and the ice crystals were nearly always deposited in a definite form on all projecting objects exposed to the air. The peculiar characteristics of these "fog crystals" were:—

(1) They were deposited in disproportionately greater amount on the windward side of these projections, and at times were even entirely lacking on the lee side.

(2) When the deposition was accompanied by a fog, the latter was always a light one through which the sun could be seen. In the cases observed on the Barrier, a white fog bow could usually be seen in the opposite quarter to the sun.

This last fact is of peculiar significance, in that these white fog bows can occur only in the presence of waterdrops,* so that we may have here evidence of water, still liquid, at temperatures down to $-10°$ F.

Before the question of snowfall is left, it seems desirable to point out that definite falls of snow from isolated clouds did not commonly occur within the limits of our experience at Cape Evans. At Cape Adare, however, in the summer, this type of snowstorm was of much more frequent occurrence, and this may perhaps be correlated with the greater prevalence of open water at that station.

Precipitation from Moist Winds Blowing from the Open Sea.

By far the greater proportion of the visible snowfall at such stations on the coast of the Antarctic as Cape Adare must be attributed to light sea breezes which have

* Or spheres of ice. In any case, the spheres, whether of ice in the amorphous form or of water, are of higher energy content than crystalline ice, and this may be due to a poverty of condensation nuclei in the air. Bentley also points out that the first crystals formed in freezing water are of circular section, and that the star-shaped forms do not develop until a later stage in the growth is reached. (*See also* footnote to p. 51.) Small spheres of ice have been observed to form from tiny waterdrops condensed on a microscope slide, the subsequent change to definite crystalline forms being comparatively slow. Beilby has observed such icedrops to crystallise on being touched.

been warmed and have had their vapour content increased by their passage across extensive stretches of open water. Specialised examples of this type of precipitation are the deposition of hoar-frost, which occurs in connection with the appearance of frost-smoke over open leads and pools when the temperature is low. Perhaps the best example within the experience of the present expedition was afforded at Cape Adare, when, on August 16, the whole of the sea-ice north of Robertson Bay was torn out during a hurricane, and a lead of open water a mile and a half to half a mile wide, and some twenty to thirty miles long, was formed. The blizzard which did the damage was succeeded as usual by light airs from the north-west, and the frost-smoke which had formed in great quantities as soon as the lead opened was blown towards and over the beach, so that the whole winter station was enveloped in fog so thick that for some time Cape Adare was invisible from the hut. This was the first opportunity afforded of making certain of the composition of the frost-smoke clouds which had so frequently made their appearance to the north during the preceding few months. This fog proved on examination to consist of a mixture of minute ice prisms, similar prisms with granular aggregates attached to them, and immature star-shaped crystals, in fact very much the same type of snow as had fallen many times before, when fairly low temperature had coincided with the occurrence of a saturated or nearly saturated northerly breeze.

The proportion of snow which owes its origin to these sea breezes will naturally vary in different situations, but it seems probable that it is this factor which causes a considerable portion of the greater precipitation which is a characteristic feature of the more northern regions of the Antarctic continent.

If we consider, for instance, the stations with which this memoir primarily deals, it will be evident that the amount of snow derived from this source must be much less at Cape Evans than at Cape Adare. The reason for this statement is easily seen. Cape Evans with its more southerly position is nearly surrounded by high land, while McMurdo Sound is seldom open for more than two or three months in the year. The only region where open water may reasonably be expected to occur in a normal winter is to the north-east, where the Cape Crozier basin lies.* Surface winds from this direction are rare, and, in any case, the northern slopes of Erebus and the peninsula of Cape Royds are interposed between Cape Evans and the Crozier waterhole.† True sea-breezes, therefore, are in a normal year practically confined to the months from December to March or April. Even during these more genial months, the Ross Sea is often crowded with pack, and the amount of open water traversed by the air is therefore often comparatively small.

At Cape Adare, on the other hand, we have a situation which differs from that of the stations on Ross Island in many essential respects. The peninsula, in the lee of which the station was erected, is surrounded on three sides by sea, and only on one side

* It seems more than probable that the heavier snowfall (compared with that in 1911) at Cape Evans in 1912 was directly associated with the fact that the sea in the outer portion of McMurdo Sound did not freeze over in 1912.

† Maps III and V.

—that bordered by Robertson Bay—was the sea-ice at all permanent in 1911. During the whole of the winter of that year the pack in the Ross Sea was seamed with waterholes, and we had constant evidence in the shape of rolls of cumulus cloud and patches of frost-smoke, that much more extensive leads of open water existed to the north and north-west. Indeed, it seems probable that at no time was the main body of the open water more than fifty or a hundred miles distant from the Cape for many days at a time.

Conditions at Cape Adare should, therefore, have been eminently favourable for the occurrence of the particular type of precipitation we are now considering, and this proved to be the case. During March and April, while the sea to the north remained entirely open, a considerable quantity of snow fell, almost all in calm weather or with a light north-westerly wind. The clouds in almost every case could be seen gathering out to sea, and at times as many as six snow-squalls could be seen at the same time around the horizon between N.W. and N.E. These snow-squalls would move slowly towards the south, and many of them passed over the beach on which our station was situated. The largest falls in these two months—5¼ inches on March 10, 2 inches on April 4, and 3¼ inches during the night of the 26th—were all of this type.

The first half of May was marked by strong southerly winds, and, after these had ceased, the temperature fell so low that the sea froze over quickly. The result proved to be an immediate diminution in precipitation, and these conditions lasted throughout May and June. In July the waterholes again commenced to open up, and it can hardly have been a coincidence that the snowfall immediately showed a marked increase. It seems probable that the open-water surfaces were sufficient to saturate the air near them, while a continual succession of light airs kept up a free circulation in the atmosphere and so prevented the formation of a number of distinct isolated areas of precipitation. Whether this was the case or not, July and August were marked by continual precipitation, much of it in the form of hoar-frost. In November and December, when summer conditions had once more set in, the correlation of calm weather and westerly airs with comparatively heavy snowfall was again most marked. Time after time, the remark "Calm or north-westerly airs" occurs in the meteorological log side by side with the record of falling snow. Certainly there can be no question but that this type of precipitation, while mainly restricted even here to the summer months, was responsible for the greater portion of the snow which fell during the year 1911 at Cape Adare.

At Inexpressible Island, the station of the Northern Party during the year 1912, a large waterhole was kept open by the prevalent westerly gales during the whole winter. The gales, blowing as they did directly from the cold plateau, were usually devoid of snow except in the first few hours. Only on two or three occasions during the winter was the snowfall in this district at all heavy, and each of these occasions was characterised by a south-easterly wind of medium strength. These winds must have crossed the open water before they reached the drift in which the Living Cave had been dug.

During the six weeks of summer sledging which preceded this winter, only three snowstorms of any magnitude occurred in this area. Each of these, however, was

unusually heavy, 12 to 17 inches of snow being recorded on every occasion, and each was directly connected with the presence of open water to the east. Clouds gathered to seaward, moved slowly inland, and the snow was precipitated when the clouds came in contact with the mountains above the camp or with Mount Melbourne.

A special case of the precipitation of snow in calm weather was well seen on the west side of Robertson Bay, and here it is probable that the conditions observed in 1911 are normal, and may be expected to recur from year to year. The abrupt rise of the Admiralty Range and its immature dissection along this stretch of the coast, have

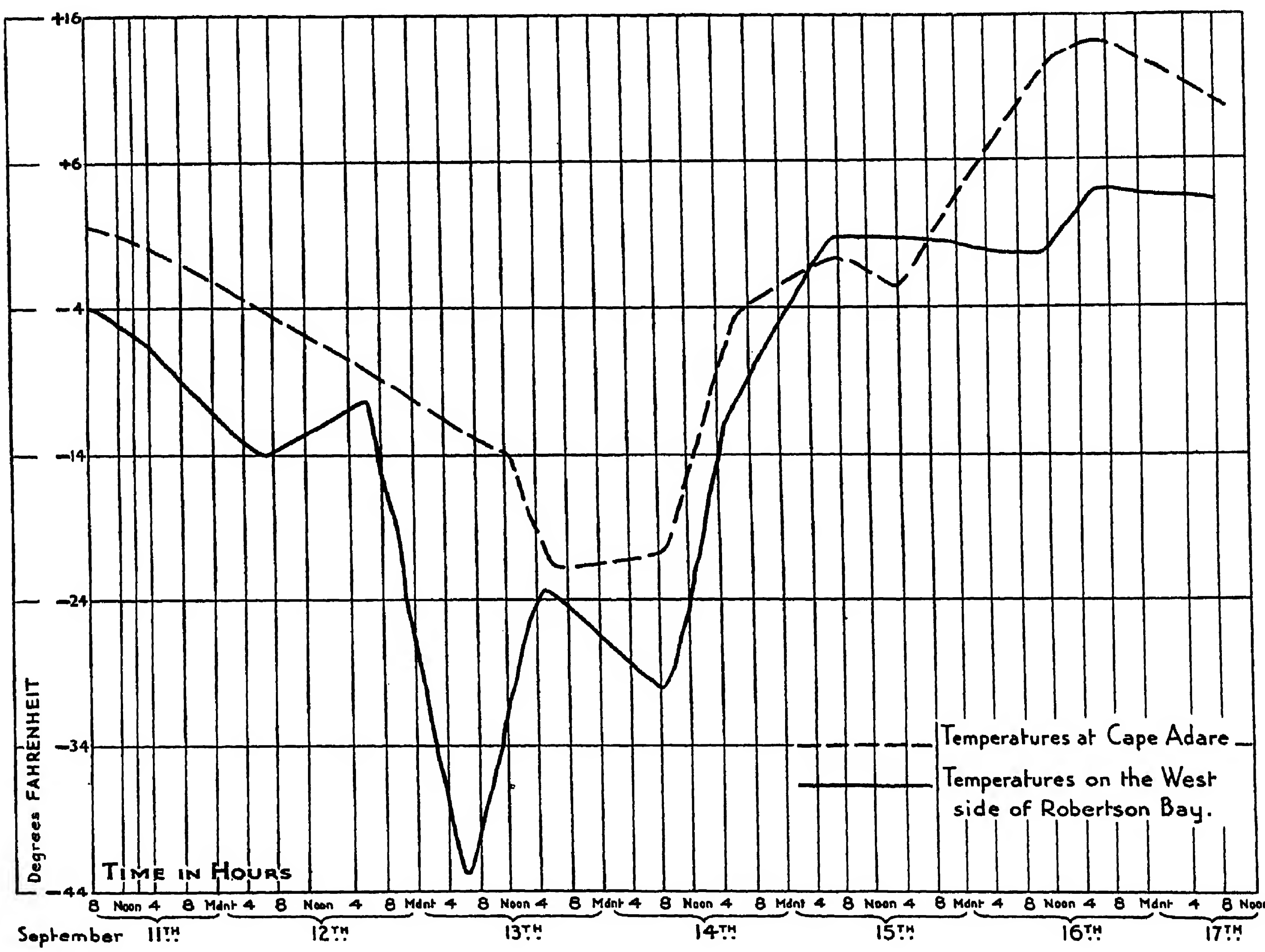


Fig. 6.

caused the formation of an area of calms bordering the coast-line. Here the air is undisturbed by the fierce and long-sustained gales which characterise the weather of the east side of the Bay. These gales have a distinct effect on the snowfall of the calm area, for the air they bring to the west is at a high temperature and has a relatively high water-vapour content. When this meets the colder air of the calm belt along the west coast, a veil of snow is formed all along the border of the latter. A comparison between the uncorrected temperatures at Cape Adare and those on the west side of Robertson Bay during and before such a gale is shown in Fig. 6. From the deviations of the sledging temperature curve from that obtained at Cape Adare and

from the abrupt troughs in the former, it will be clear that here are conditions favouring a relatively heavy snowfall. That this was actually the case was demonstrated by the presence of loose snow 3 or 4 feet deep on the sea-ice in the bays at the back of the calm area (Plate VIII). Further evidence in favour of the same contention was to be seen, as will be shown later in this memoir, in the structure of nearly all the glaciers on this side of the Bay.

The facts cited above are sufficient proof that a considerable portion of the Antarctic snowfall at Cape Adare takes place in comparatively calm weather, and that the material is largely derived from the neighbouring sea. If further proof were required, many similar examples could be adduced in support of our contention. It remains only to emphasise the fact that it is to this source of snowfall we must chiefly look to explain the areas of greater precipitation that at first sight seem to form exceptions to the general rule which would range Antarctica amongst the desert continents.

(5) Amount of Precipitation.

Of chief importance to the study of the Glaciology of any region is the amount of snowfall in the place under consideration, *in comparison with* the amount of snow or ice removed by ablation, melting, wind and other denuding agencies. It is the difference between the two, rather than the actual amount of either, that is effective in promoting or reducing glacierisation.*

The estimation of this quantity is a matter of exceeding difficulty, for as a rule the fall of snow cannot be measured in a cylinder similar to a rain-gauge, because it is often accompanied by considerable wind; and, as mentioned above, it is almost impossible to distinguish between true snowfall and detrital snow carried by blizzard winds. A quite common occurrence in the Antarctic is to find that, after very thick blizzards lasting for three or four days and carrying very heavy drift, the net result is, not a deposition, but a denudation of the former snow surface. It is therefore only in certain places that one is able to make any estimate of the amount of snow added to the surface during the year.

Of these estimates the best authenticated is due to an observation by Joyce in January, 1909, on the Ross Barrier, when he rediscovered Captain Scott's "Discovery" Depôt A, after an interval of six years, four and a half months. The depôt was by this time almost completely covered, and the superficial deposit indicated a mean annual excess of snowfall over precipitation of 13 inches of hard snow of density about 0·5, a quantity equivalent to 7½ inches of rain per year.†

A much rougher estimate of the snowfall may be derived from the amount of snow found on the sea-ice between Cape Evans and Hut Point, just before the break up of the sea-ice, or about ten and a half months after its formation. At this time the sea-ice here is covered with large dome-shaped sastrugi up to 3 feet high, and with an average height which we have estimated as about 14 inches of hard snow, whose density cannot

* 'Glacierisation—The Inundation of Land by Ice,' *see* Chapter V, p. 131.

† E. H. Shackleton, 'Heart of the Antarctic,' vol. 2, Appendix V.

be far from 0·5. This estimate can make no pretence to great accuracy, but we may take it as representing an excess of deposition over denudation for the year of between 8 and 20 inches of this hard snow.

At Cape Adare, also, the accurate calculation of the amount of snowfall proved impossible; and, indeed, had it been possible, it would have been of little practical significance. Not only was the Cape itself kept free of snow by the gales which swept it periodically, but also the beach on which the hut was erected, and the whole of the sea-ice on the east side of Robertson Bay had retained no snow at all at the end of December, when our observations were discontinued. It is probable that some 80 or 100 inches of soft snow (corresponding perhaps to 12 inches of rain) fell in the neighbourhood of winter quarters during the ten months the station was occupied, yet the Cape and its surroundings were as bare of snow when left as when first occupied.

The case of the west side of Robertson Bay was, as already stated, very different. During the period May–September, 1911, between 36 and 48 inches of snow had accumulated on the sea-ice in the back of Relay Bay, the Bay of Bergs, and Pressure Bay. This snow had not been compacted by wind, but it is probable that it had sunk somewhat under its own weight, and through molecular readjustment. Probably it represented as much as 70–80 inches of the light fleecy snow which falls in the Antarctic autumn and winter. In all likelihood this 70 inches represents decidedly less than half of the annual snowfall in the region. Confirmatory evidence in favour of this is afforded by the fact that permanent snow deposits are undoubtedly being added to the glaciers of this region.

Nowhere would it be possible to find a more striking object-lesson of the folly of generalising about the Antarctic climate from isolated data, than is provided by a comparison of these two districts existing side by side in Robertson Bay. To the east we have denudation holding uninterrupted sway. The glaciers are decreasing rapidly in size, such snow as falls during the year being immediately swept away by the winds. To the west, on the other hand, we have a steady snowfall, only slightly greater than that on the east, which yet succeeds in holding its own.

We have little other evidence enabling an estimate to be made of the amount of snowfall along the west coast of Victoria Land. At Evans Coves,* as might be expected, the snowfall recorded in 1912 was distinctly less than that which occurred at Cape Evans or at Cape Adare the previous year. This may be attributed to the prevalence of dry westerly winds blowing continually from the plateau. As these winds approached the coast they would suffer a rise in temperature due to their descent. The gales, therefore, could not deposit moisture. It was only when a local reversal in direction of the wind took place that heavy snowfall occurred. Then the southerly wind would force its way over to Inexpressible Island, having first traversed the Evans Coves' waterhole and so replenished its supply of moisture, and the forced rise of this air would cause a snowfall of greater or less magnitude. During the whole of our stay at the island, less than four feet was added to the drift in which the cave was excavated, and this was obviously immensely more than the average fall for the island, being chiefly drift-snow collected

* Map XIV.

in a lee. Inexpressible Island, like Cape Adare and Cape Evans, must be added to the list of the districts where deglacierisation is taking place, the difference—precipitation less denudation—being a minus factor.

A further estimate may be made, based on the thickness of snow deposited on the pack-ice in the Ross Sea. This estimate is complicated by the fact that our knowledge is so scanty regarding both the time which has elapsed since the first formation of the pack, and the amount of raising or lowering of the water-line level, due to the weight of the superincumbent layers of snow and the consequent flooding of the lower portion of the snow by sea-water. For this reason, and since the period elapsed since the first formation of the floes is unknown, it does not seem that any useful information can be obtained from this source. It is clear, however, that the snowfall on the pack-ice in the Ross Sea is much less than that observed by Drygalski* near the Gaussberg or by Wordie† in the Weddell Sea.

It seems best for purposes of calculation to use the single observation which was made on the Barrier, which has the advantage of applying to the mean of a number of years. We will, therefore, assume that, on the Barrier, in the vicinity of Minna Bluff,‡ there is a yearly excess of precipitation over denudation equal to 7½ inches of rain. What the actual total precipitation may be is even more difficult to estimate, but judging by the amount of snow which may disappear in the summer, between the successive blizzards, the total precipitation here cannot be far from 1 to 2 feet of *water* per year.

A point of some importance is the relative amount of snow precipitated during the different seasons of the year, and this is especially vital from the point of view of the temperature conditions corresponding to the period of maximum glaciation.

For Cape Evans and places in its vicinity, the statement may be made that, excepting the three summer months, the greatest amount of precipitation appears to take place in the spring. In any case it is from the first of October to the end of November that the quickest growth of snow takes place on the sea surface.

Further, the general statement can be made that more snow is permanently added to the surface in the warmer months than in the colder part of the year. At least three causes are probably operative in producing this result—

(1) a greater snowfall,
(2) a lower summer wind velocity, and
(3) a higher temperature.

Both of these last are operative in preventing deposited snow from being swept away by wind.

The records from other stations occupied by the present Expedition are very fragmentary, for at no other station did a party spend a complete twelve months. All the records obtained, however, point towards a heavier snowfall in summer. This was markedly the case even when, as at Cape Adare, the results were complicated by the

* Drygalski, E. von, 'Arch. Sciences phys. et nat.,' Genève, tome xxx, October, 1910.

† Wordie, J. M., 'Trans. Roy. Soc. Edin,' vol. lii, Part iv (No. 31).

‡ Map III.

occurrence of sporadic leads and waterholes throughout the year, with consequent increase of the precipitation in the winter months during which these leads were open.

During the short summer campaign of the Northern Party, in the neighbourhood of the Campbell and Priestley Glaciers, three snowfalls, ranging from 12 to 17 inches each, were recorded within six weeks in January and February, 1912. These falls were unusually heavy for the Victoria Land sector of the Antarctic, and yet the winter snowfall in the same region was quite small.

Observations by other Antarctic expeditions are in general agreement with this, as will be seen from the following Table :—

——	Gourdon.	Arctowski.	Shackleton.
Spring	110·6 in.	71 in.	
Summer	122·1	66	
Autumn	67·3	65	
Winter	76·5	69	
Year	376·5	271	230*

In review, the following points appear to be substantiated :—

(1) The amount of snowfall depends to a great extent upon the local meteorological and physiographical conditions, two areas side by side often showing enormous differences in snowfall.

(2) The snowfall at Cape Adare and at stations on the edge of the continent near the polar circle is greater than that observed further south in McMurdo Sound, on the shores of the Ross Sea and on the Barrier.

(3) The best substantiated figures refer to the annual deposition on the Barrier, which is probably not far from 12 to 24 inches of water, of which 7½ inches is annually added to the surface, the remainder being lost by ablation and other causes.

(4) Not only is the snowfall greatest in spring and summer, but conditions are such as to ensure that this summer snowfall is much more likely to form a permanent addition to the surface than that which falls in autumn and winter.

Though the adopted value for the yearly excess of precipitation over evaporation (7½ inches of water) is not large, it is still of sufficient magnitude to account for the present glacierized condition of the continent. It should be remembered, however, that this 7½ inches refers only to those flat snow surfaces which are clean and situated well away from any silt or rock outcrops. As will be seen later, the presence of such foreign substances exerts an enormous influence on the amount of melting or evaporation—so true is this, indeed, that in the presence of large quantities either of silt or of rock, denudation may be very considerably in excess of deposition.

* Seasonal figures not available.

The three main agents which tend to modify a snow surface after its deposition are wind and drift, temperature, and internal change of structure. These will be considered separately as regards their action on the snow surface, and, so far as possible, without reference to their effect on the denudation of the surface, which is dealt with in another Chapter.

(1) *Modification by Wind and Drift.*—We shall first deal with modifications produced by the wind at the time of the deposition of the snow. Mention has already been made of the sastrugi, or wind ridges and furrows; and it is essential to draw a distinction between the sastrugi which are due to deposition or addition of snow to the former surface, and those which are caused by the erosional action of the wind. Under the former heading come, not only the large sastrugi as generally understood, but also the ripple marks on the snow surface, the drifts on the lee and windward side of obstacles, and snow cornices.

In general it may be stated that the principle upon which the *formation* of sastrugi depends is that a critical wind-force is necessary at any spot on the snow surface to keep the snow from coming to rest. This critical force must have a definite value for dry snow for each definite weight and shape of snow grain. Since in the Antarctic the snow, except when soaked with brine, is only wet on the rare occasions when the temperature is but a degree or so below freezing-point, the observations we have made refer only to the case of dry snow.

On a uniform level snow surface, if the wind were of uniform force, we might expect that the top surface would be covered with a mass of small crystals rolling uniformly along with the wind, while all crystals above a certain size would be at rest.

In reality, however, the air moving along a surface is in turbulent motion; so that eddies, dependent in size on the wind force above and away from the ground, are formed along the surface.

If the snow is falling with wind, the result is that deposition will take place chiefly in places where the wind velocity is downwards, and thus a series of ripples are formed on the snow surface whose distance apart is equal to the distance between the successive eddies (Fig. 7; Plates IX, X and XI). Since also the eddies are moving forward with the wind, the ripples in the snow move forward also.* The mechanism of this movement consists in an abstraction from the windward side of the ripple and a deposition on the leeward side. According to Cornish,† the rate of movement of the ripples in a wind is 2 inches per minute for a wind velocity of 30 miles per hour. Under the continued action of the wind, the

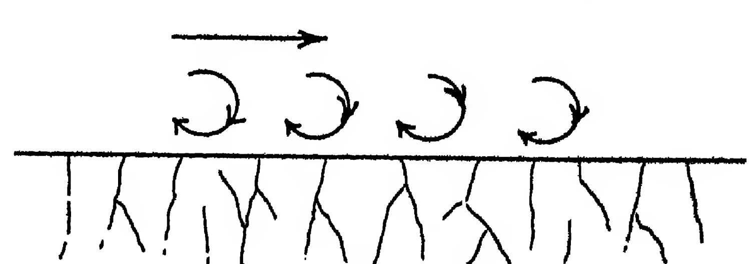


Fig. 7.

* Cornish, 'Geogr. Mag.,' 1902, p. 137.

† *Loc. cit.*

drifting snow gathers together in heaps on the surface and, finally, forms the normal form of deposition drifts which are indicated in vertical section in Fig. 8. In plan they are longer than they are broad. Cornish* gives a very good description of the sequence of events, during the change from the approximately level ripple-marked patch, to the smoothly-rounded dome, or horseshoe-shaped drift, or barchan (Fig. 9).

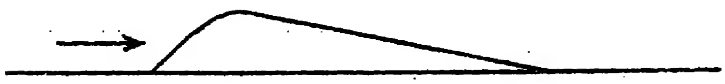


Fig. 8.

With us in general the barchan type occurred only rarely, and the nearest type of deposition drift to the barchan was the simple dome-shaped drift with slightly steeper slope facing the wind. This type of sastrugi, however, was never common with us except in two restricted districts, within whose limits the sastrugi were almost all of this form. The two districts were the stretch along the sea ice from Glacier Tongue to the Barrier, and from Corner Camp for a distance of about 20 miles in a southerly direction. Both these stretches seem to be positions where the wind blows almost continuously, though not with excessive violence. In both areas, the surface is exceptionally hard and favourable for sledging.

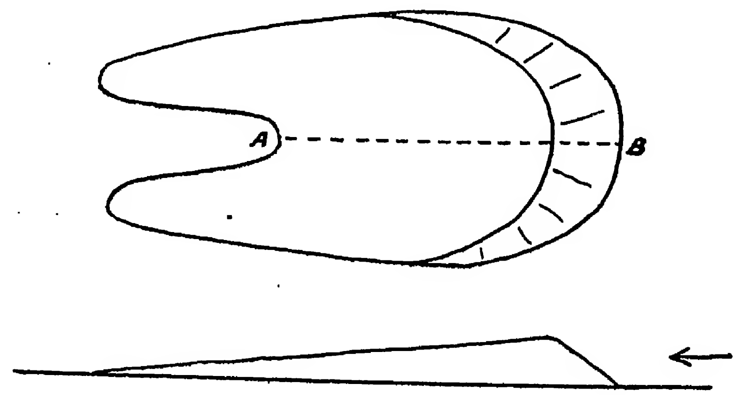


Fig. 9.

A study of such a surface in the rays of the low spring sun is of exceptional interest. Looking in the direction of the sun, the old polished patches of snow show a distinct yellow sheen; newer patches, a faint yellow sheen; later patches, still, have a distinct bluish tinge; and the very latest drift has quite a violet hue. This effect is probably due to the different sizes of the crystals forming the surface layer. In the oldest patches, the crystals are sufficiently large to form an almost icy covering and to give a fair reflection of the sun's rays, while in the case of the latest drift with smallest crystals, the light reaching the eye is largely that reflected from various points of the blue sky. The surface in these two regions, in the spring and summer at least, is wholly covered with the dome-shaped sastrugi, and the formation of each new drift appears to take place in the depressions or hollows between those already existing, somewhat as in Fig. 10. The maximum observed height to which this form of sastrugi attained in the course of nine months was 4 to 5 feet.

Fig. 10.

In the above, we have assumed that the whole action of the wind is depositional in character, though it is clear that, in general, deposition may take place in one portion of the sastrugus, simultaneously with denudation in another part. It will also be clear that, normally, we have to deal with crystals of different sizes and weights, and therefore

* *Loc. cit.*, p. 155.

that the smaller crystals (of lately fallen snow) can only come to rest in places of the least wind velocity, or in the hollows and on the lee tail of the sastrugi, while the heavier forms may be deposited closer to the windward portion of the drift. Since the sastrugus of this type usually grows in height during the course of a blizzard, the growth must occur by the lodging of the heavier grains on the upper surface close to the windward slope, and the addition of smaller grains in the lee.

The actual motions of the different crystals may be seen at times, and was particularly noted on November 25, 1912, during the return of the search party. At this time, terraced sastrugi were being formed as in Fig. 11 and Plate XII. The drift was low and never rose more than 3 feet from the ground, and the wind velocity was from 20 to 25 miles per hour. A little above the surface of the Barrier, the finer and lighter snow crystals were being carried uniformly along with the wind with a velocity of many feet a second, while the larger and heavier grains were slowly rolling along the uneven surface at the rate of a few inches a second. It was evident that the distinctive forms of the sastrugi were due to these heavier and more slowly-moving grains. They could be seen moving slowly along with the wind, being deflected or stopping as they met obstructions, and continuing on their way once more when the wind increased in violence.

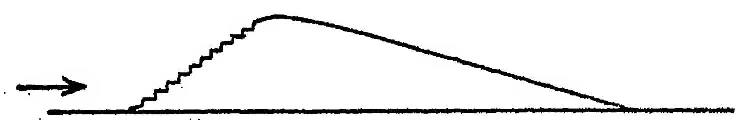


Fig. 11.—Section of terraced (erosional) sastrugus.

Before leaving this subject, it should be pointed out that the forms assumed by these drifts are in general agreement with the principle that the drift will take such form as will present as little resistance to the wind as possible, that is, a form in which the greatest thickness is nearest the windward side of the drift.*

The question at once arises—Why is this form not maintained during the process of erosion of the drift? This must be due to the fact that the process of erosion is not similar to that of deposition; it is not carried out by an erosional action dependent on the wind pressure alone, but is due to a much greater extent to the mechanical chiselling action of the drift snow. (That this chiselling action may have very considerable effects, even in eroding ice, will be seen later.) If the action of erosion were not of this type, it is obvious that the erosion would always be least at the lower levels, where the velocity is least, whereas, in the case of the undercut-sastrugi of denudation, which will be mentioned later, the action has certainly been greatest at the lower levels where the heaviest granules, which are most effective for mechanical denudation, are kept in motion.

* The resistance of an obstacle to wind and the amount of eddy motion caused by the obstacle is least when the latter is of streamline form, the resistance and turbulence being greater the more widely the streamline form is differed from. Since the amount of deposition is chiefly dependent on the degree of turbulence in the air-stream, it is not unreasonable that the drift should be deposited in such positions and amount as will cause the streamline form to be approximated to. (*See also* E. Karrer, 'Journ. Franklin Inst.,' December, 1921.)

Further evidence is furnished by observations of the manner of this erosion on a dome-shaped sastrugus of deposition. The first step is the accentuation of the windward slope of the dome and the formation of steps or terraces, as shown in section in Fig. 11. In the course of time, accidental irregularities in the shape of the windward face cause a local concentration of the wind, and these positions become more and more eroded. They finally take on the form of re-entrants, until, in the second stage, the stepped and terraced appearance becomes equally marked in plan as formerly in section (Fig. 12). The points to be particularly noted with regard to this form are the straight edges A and B, and the sharp ridges C and D, on the upper surfaces of the erstwhile gently convex top. In the course of time, the bays E become more and more pronounced, and finally cut completely through the drift and leave it in the form of long sastrugi directed parallel to the wind, and of shape somewhat as illustrated in Fig. 13 and Plate XIII.

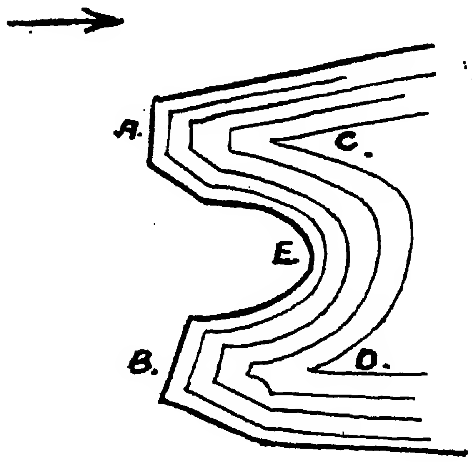


Fig. 12.

A modification is commonly to be seen when sastrugi of this type have not yet reached their full development. They then assume the form named by us "marbled" sastrugi (Plates XIV and XV).

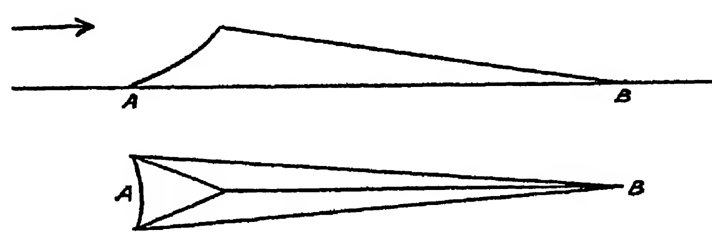


Fig. 13.

One of the most striking forms the sastrugi can take is observed when a surface which has for some time been hardened by exposure to wind and weather is finally eaten into by the drift. Here the upper crust is sufficiently hard to resist the attacks of the wind and the drift, while undercutting of the front and sides takes place to a truly remarkable extent,* until the sastrugus is as shown in Plates XVI and XVII, the tongue being left with so little support that it often bends downwards or breaks under its own weight. It is the common occurrence of this form which particularly leads to the idea that the sastrugi of erosion are due rather to the chiselling action of the snow grains carried by the wind, than to the force of the wind itself, since it is along the lowest channels of the surface that the heavier grains will be rolling.

As regards the actual amount of snow that can be eroded by the blizzard, more will be said later, and we will content ourselves here with the statement that 18 inches of hard snow surface have been observed to disappear completely in the space of a short 12 hours—a rate of denudation which is higher than the observed rates of deposition of snow in these same places. Before leaving this point, however, emphasis should be laid on the fact that sastrugi formed by deposition during snowfall consist in general of small floury crystals, which are fairly soft under foot and which do not form a good sledging surface. On the other hand, those due to the prolonged action

* Fig. 24, p. 43.

of wind carrying only drift, consist in general of the harder and more resistant portions of the original surface. These form a good sledging surface, except in cases where the sastrugi are long and narrow, and so high as to cause steep gradients, and hence demand particular exertions and precautions in order to prevent the sledges from capsizing.

Drifts in the Vicinity of Obstacles.

In the above remarks on the subject of sastrugi, no mention has been made of the formation of snow-drifts in the vicinity of obstacles. It seems desirable here to deal with this point also, since the deposition of snow under locally modified conditions can reach dimensions immensely greater than on an open and almost level surface. Plates XVIII and XIX illustrate this well.

As in the case of the formation of the sastrugi of deposition, deposition in drifts in the vicinity of an obstacle is conditioned by the eddies and irregularities in wind velocity caused by that obstacle.

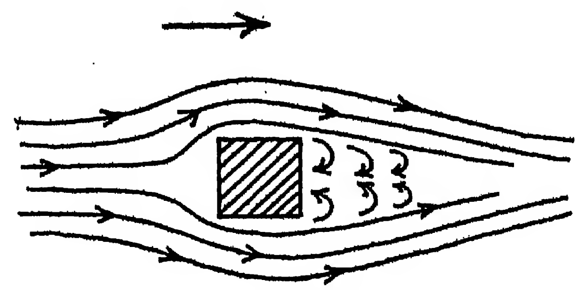


Fig. 14.

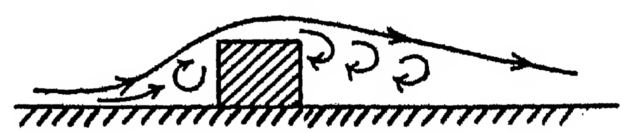


Fig. 15.

The simple case of a small obstacle of dimensions only a couple of feet each way presents little difficulty. In plan and section, the directions of the wind are shown in Figs. 14 and 15. Where eddies occur the average wind velocity is less, and the snow is, therefore, deposited in these positions to form drifts, which finally assume the form shown in Fig. 16. These drifts are similar to the normal type of sastrugi of deposition in having a steeper slope in front than behind, the point of greatest height (the obstacle) being very much closer to the windward than to the leeward side.

Where the drifts reach a considerable size, such as those formed near the Winter Quarters at Cape Evans and Cape Adare around the stranded bergs imbedded in the

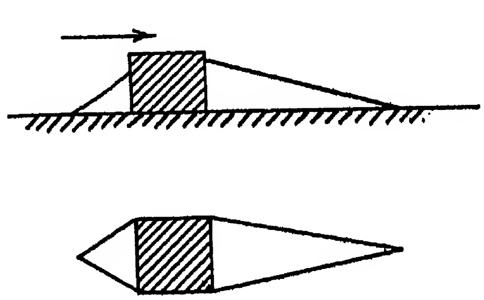


Fig. 16.

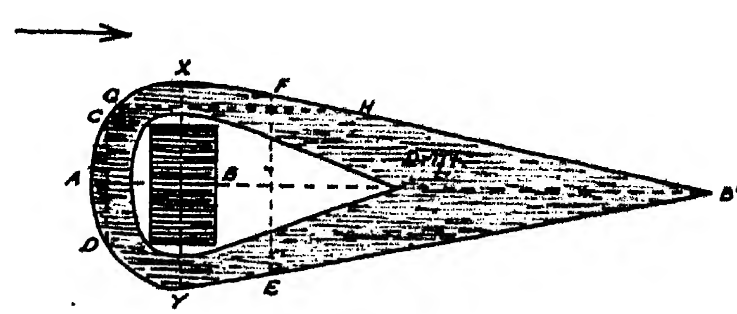


Fig. 17.

sea ice, the forms assumed by the drift are much more complex. The drifts that form around these bergs are, at first sight, of peculiar shape. The drift to windward is represented in plan in Fig. 17 ; it is of fairly gentle slope, and may grow by the latter part of winter to a depth of 10 feet or so. The form of this slope along the line AB is illustrated in Fig. 18, which shows that an unfilled gap is left between the berg and the drift,

with usually a small overhanging cornice on the leeward edge of the drift. During the course of the winter, the drift grows in size, but—for a considerable deposit on its surface—moves only a little closer to the berg. Finally, if the drift snow has been sufficiently heavy during the winter, the drift may move right up to the berg so as to close the gap completely. In general, we may say that the rate of closing of the gap is slow, until the cornice becomes sufficiently close to make this region one of relative calm, after which the drift fills it up very quickly. Since the strength of the wind in this "wind-gully," as it has been called, is dependent on the height of the berg forming the obstacle, it is easily seen that it is only for the lowest icebergs that it will become completely closed during the course of one winter.* A section along the line CD is shown in Fig. 19. In addition to the wind-gully on this side of the berg, lateral gullies are also developed at the

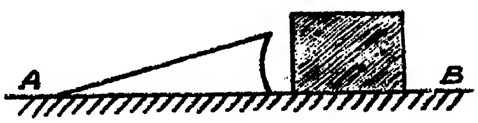


Fig. 18.

Fig. 19.

sides, and these do not usually fill with snow during the course of the winter. The section XY is drawn in Fig. 20, to show the form of these drifts. These "wings" extend a considerable distance to leeward and are shown in section in Fig. 21.

One of the points about these drifts, which at first sight appears very curious, is the large area of bare ice in the lee of the bergs; whereas the sea ice in the open has generally a few inches of snow on it. In the neighbourhood of Cape Evans, such bare patches extended a full half-mile to leeward of all bergs (of height, say, 50 feet) and these patches remained free from snow throughout the course of the whole winter. By observation we know that the wind velocity here is very much less than in places away from the shelter of the berg, and the absence of drift can only be due to upward air currents over this region, the air for these currents being probably supplied from the

Fig. 20.

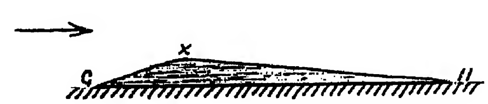


Fig. 21.

lateral wings. Since the upward draught cannot be of any great force, the phenomenon bears eloquent testimony to the small amount of precipitation during calm weather, as distinct from drift precipitation, during the winter months in McMurdo Sound.

It should be noted that no bare patches of this nature were recorded in the neighbourhood of Cape Adare. In this latter region, great numbers of bergs of all sizes were stranded on the shoals off the end of the Cape, and these were later included in the sheet of sea ice which covered the sea during the winter. From the time that the sea ice was thick enough to bear the weight of a man, these bergs were kept under observation by the members of the Northern Party. In the case of the largest bergs, with

* The gap does not close during a single season in the neighbourhood of Cape Evans or Cape Adare unless the berg is quite a low one.

a height of from 50–90 feet, it was usually found that a small loose drift was situated immediately to leeward of the bergs, long drifts of compact snow occurred at either lateral extremity of the lee, and a long hard drift of the type described in a preceding paragraph tailed away to windward. So far the drifts tally very well with those seen at Cape Evans, but there was no bare space stretching half a mile or more to leeward; on the contrary, a space of similar size would be marked by the presence of a considerably greater amount of snow than existed on the clean-swept sea ice of the unsheltered situations on the east side of Robertson Bay. The soft uncompacted nature of this snow vouched for the lighter character of the wind in this area, while deposition was taking place.

It seems probable that the discrepancy between the observations at Cape Evans and at Cape Adare is quite naturally explained by the assumption of a greater snowfall during calm weather at the latter station. Earlier in this chapter, prominence has been given to the excess of snowfall in calm weather over "blizzard snowfall," along the more northerly portions of the Antarctic coast, where open water plays an important part throughout the year, and where north-westerly and northerly winds blowing off the sea are to be expected. At Cape Evans, on the other hand, snowfall of appreciable amount in calm weather seems to be the exception rather than the rule, and the amount is not sufficient to make up for the loss sustained through the removal of snow which takes place under the influence of ablation. In such a case, if the "blizzard snowfall" and the detrital snow carried by gales are prevented from depositing in any particular spot, clear spaces might easily be formed.

Another type of clear space, however, is undoubtedly common to all regions of the Antarctic where favourable circumstances exist. We refer to those which are the direct result of "funnelling." Wherever two obstacles occur close together in the path of the prevalent strong wind, the air is "funnelled" between these obstacles, and the erosive power of the snow-drift it carries is, therefore, much increased. In all regions where strong winds exist, such clean-swept spaces occur, and they are especially a feature in areas of pressure ice and of sea ice where bergs are common. Perhaps the best example known to us is that between Dunlop Island and the mainland of South Victoria Land. Here the sea ice is swept almost, at times quite, clear of snow for a length of 3 miles or more, and for a width corresponding to the breadth of the channel.

Even behind small obstacles of about 10 feet cube, the general form of the snow-drift is maintained, the two wings extending a full 200 feet before finally merging.* Quite commonly for obstacles of about this size, a small drift is formed in the position X (Fig. 22), but this never attains any great size. The maximum thickness of the drift, in the case figured, is about 4 to 5 feet of hard snow.

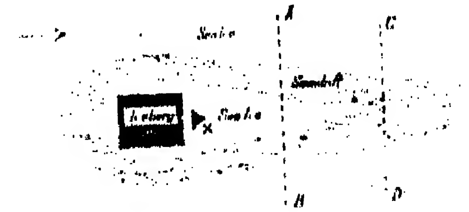


Fig. 22.

* Obviously these drifts will be developed in their best form in situations where the wind does not vary in direction.

One of the most striking of the effects we have noticed in the Antarctic connected with the formation of drifts, is that of drift formation on the lee side of hills. If, at the beginning of winter, the rock slope (say, of 25° slope) is bare, a drift is formed with the advent of the first blizzard. This at first grows in depth with remarkable speed, but with each succeeding blizzard grows more slowly, till finally a critical slope is reached, after which no appreciable further increase in depth takes place.

We have, unfortunately, few observations of the gradient of this critical slope, but in the case of the drift at Evans Coves, in which the Northern Party made their winter quarters in 1912, it was approximately 10°, or a rise of about one foot in six. At Cape Evans, the gradient was on the average about one in seven.

Owing to the enormous amount of drift snow carried by the wind, the precipitation in the lee of such obstacles is very heavy and, under favourable circumstances (for instance, in the lee of the small 8-foot bank of ice into which the pendulum cave was exacavated), would attain a thickness of about 6 feet in twelve hours. This was a source of considerable trouble, while the cave was in use, as this 6 feet had to be excavated after each blizzard before the cave could be entered. While this quantity of drifted snow was being deposited in such sheltered positions, however, the deposition in the open would seldom be more than 2 or 3 inches, and was quite generally a minus quantity.

From what has been said above, concerning the formation of drifts behind obstacles, it will be clear that all pronounced hills will, during the course of the winter months, collect in their lee drifts of considerable magnitude—of such magnitude indeed that the melting and general ablation during the summer may be unable to remove the winter's deposit of snow (Plates XVIII and XIX). This growth, we know, will have been very quick in the first stages of its formation, and will become much slower as the critical slope is approached. When, finally, the critical slope of the drift is reached, the snow-drift will cease to grow, and will then vary in thickness and in gradient about a mean value—the maximum thickness occurring in winter or spring when the drift has a slight snow-covering, and the minimum in early autumn consequent on the consolidation of the maximum proportion of snow into ice, and the effect of the summer thaw in denuding the upper surface of the drift. The magnitude of these drifts is therefore determined by the size of the obstruction to which they owe their formation. The snow is subsequently changed into ice by natural processes and they then form diminutive snow-drift glaciers or glacierets.

A special type of drift* is that often formed on the lee side of a cliff, abutting against the sea ice. Different cases may here be distinguished according as the cliff facing the sea is low (of the order of 20 feet or less) or of greater height.

In the first case, the amount of snow is usually sufficient finally to form a completed gently sloping drift reaching down to the sea ice, and continuing for some distance out on the latter. The slope of such a drift is never less than the above-mentioned critical

* The terms " drift " and " snow drift " are commonly applied both to driven snow and the deposits resulting therefrom. It has not appeared possible to avoid this dual use of the words.

slope and is generally steeper the greater the height of the cliff (Plates XX and XXI). This drift will in general continue to grow until the break-up of the sea ice in the late summer, when the sea ice floats away to the open sea carrying with it that portion of the drift which rested on it.

A description of these annual drifts will be found in the chapter devoted to the discussion of the Antarctic Icefoot, of which such drifts form one type.

When the cliff face is of considerable height (50 feet or more), a drift is unable to form in the lee of the cliff (Plate CXXX). In such a case some peculiarity of the wind eddies (probably an upward draught) prevents any great deposition of snow-drift on the sea ice in the lee of the cliff, the sole exception being a very small amount of loose snow which finds its way to the bottom of the cliff and there forms a series of small fan-shaped deposits. There is, however, one special mode of deposition in the lee of steep cliffs which demands some notice, although it is only of small amount. We refer to the formation of snow cornices on the upper edge of the cliffs (Plates XXII and XXIII), a formation which may be attributed to an eddy in the wind somewhat as in Fig. 23. These snow cornices are usually of singular beauty. The size to which they attain is not inconsiderable, but it is limited by the coherence of the snow and the weight of the cornice. When the moment of this weight about the point of junction becomes sufficiently large to overcome the coherence, the cornice falls and its mass is added to the small amount of snow already gathered on the sea ice or icefoot below the cliff.

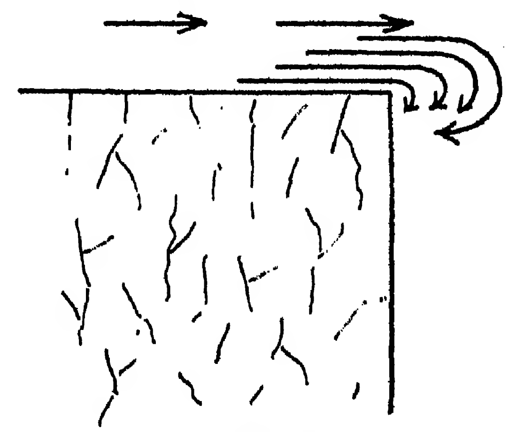


Fig. 23.

(2) *Modification of Snow Surfaces by Temperature.*—In this discussion of the effect of temperature in modifying an existing snow surface, certain points will not be treated which will come more naturally under Chapter VIII, "Ablation and Thaw," or later in this chapter. The simple statement will be made here that, on a free level snow surface away from rock, the temperature seldom rises above freezing-point (in some places never), and is generally many degrees below; so that, in the general case, as, for example, the Ross Barrier surface, these modifications are not to be compared in magnitude with the changes wrought by blizzards.

First among the modifications to be considered is the general hardening of the surface and the formation of crusts. This hardening is of peculiar importance from the sledging point of view, and takes place in two distinct ways: (*a*) under the action of wind, and (*b*) under the influence of high temperatures.

From what has been said above, it is clear that a certain amount of hardening must take place under the action of wind, for any light snow not fairly well compacted will be blown away in the winds of blizzard force. The denudation of that portion of the snow surface which is not sufficiently hardened to defy drift-chiselling, comprises indeed the greater part of the action of the wind in the formation of sastrugi of erosion. It can, in fact, be taken as an axiom that a snow surface covered with sastrugi of erosion is a comparatively hard one.

It is quite generally observed that, where drifts form in the vicinity of any obstruction, that part which forms on the windward side is harder than the part on the lee side, where the wind velocity is less; and, in the Antarctic, this appears to apply also to the case of sastrugi, either of deposition or of erosion. The weather side of the sastrugi, where the greatest slope occurs, is always considerably harder than the tail to leeward.

In Canada, it is a well-known fact that the snow which falls in the woods and forests, where the wind is slight, is very much softer than that which falls in the open, and actually has a density only about one-half of that which is deposited under the influence of wind.

In this case of hardening by wind, as well as in the case of hardening under higher temperatures, it is clear that time is a factor of no little importance. This is particularly true, however, in the case of hardening due to temperature, since time is required for the fulfilment of all structural changes. This hardening, or "packing" as it is called in Canada, is a natural process which fulfils itself at even the lowest temperatures, and is due to the growth, readjustment, and settling of the constituent crystals. This settling process is aided largely by the growth in size of some of the individual crystals at the expense of others, a growth which, as will be seen later, is a property inherent in any such agglomeration of ice crystals. This growth and the consequent adjustment continues at all temperatures, though at a significantly greater rate at temperatures close to the freezing-point.

It would appear, then, that the surface might be hardest and best packed in those cases where the individual grains are largest, but this is by no means a true statement of the observed facts. The degree of interlocking of the individual crystals is of even more importance than their size. Thus, a much harder surface is quite generally formed with the angular crystals and fragments of crystals of which the drifts in the Antarctic are usually made, than when the temperature is high and the individual grains are in the form of spheres of diameter about $\frac{3}{32}$ inch, such as occur commonly in temperate regions, and very rarely in the Antarctic. In such cases as this, where the mass is formed of hail-like granules, the coherence of the whole is so small that the least differential pressure causes the grains to move. The foot, therefore, sinks for some distance into the granular mass, however little sinking might have taken place if the same weight had been distributed over a larger area.

This case is somewhat analogous to that which one can observe on a sandy sea beach, in which there is an area of dry sand above high-water level while the lower part of the beach is wet sand sifted and packed by the water (which thus fulfils one function of the wind on the snow in the Antarctic). The depth to which one sinks in walking over the dry sand is significantly greater than when walking over the moist sand by the water's edge, and this is due, not to a difference in the size of the grains, but to the greater coherence of the mass of the wet sand, the moisture and method of packing here playing the same part as do the irregular outlines of the crystals in the typical Antarctic snow-drifts.

It has been stated that both wind and temperature tend towards the formation of crusts on the snow surface. This is daily to be observed on all sastrugi, and is shown particularly well in the case of the undercut sastrugi formed when a surface exposed to the air for some time is finally eroded by a wind of sufficient strength to take away portions of the crust and allow the wind access to the softer mass below.

Fig. 24 is a diagram illustrating one of many very excellent examples of such undercut sastrugi seen on the Campbell Glacier in January, 1912. Here they could be seen in process of formation, and the strength of the thin crust, exposed to the full force of the wind by the removal of the soft drift from beneath it, was most remarkable.

That these crusts are due in some measure to structural changes is well shown on the Ross Barrier. Here, on digging down into the surface, the snow is found to be arranged in definite layers separated, at intervals of about 9 inches on the average, by layers of air reaching a thickness of about ¼ inch and containing a very few loose crystals. This layer formation is of considerable aid in enabling one to dig out snow blocks suitable for building the pony shelter walls, as it is a simple matter with the aid of the shovel alone to obtain large blocks of roughly parallelopipedon shape, and thus to build a wall as with bricks. In travelling over the surface of snow formations of this type, it is indeed of common occurrence for portions of the surface, some hundred

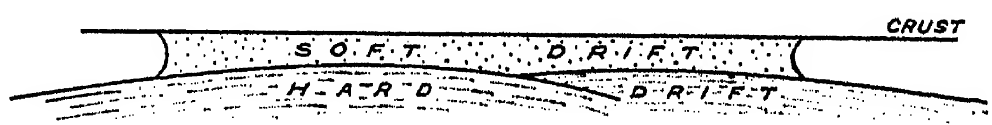


Fig. 24.

square feet or even yards in area, suddenly to sink with a curious rustling noise as the air layers are closed up by the extra weight of the sledging party on the surface.

An observation made in Pressure Bay, near Cape Adare, seems to suggest that these crusts may form on the surface of the snow even in winter when the sun is absent, and in areas exposed to little or no wind. This spot is undoubtedly an area of fairly heavy precipitation characterised by a complete absence of wind. No sastrugi or other indications of wind action were ever seen here, and it was noted on the second visit of the Northern Party to this region in October, 1911, that the footmarks left on the former occasion, six weeks before, were exactly as they were when made, with no indications whatever of wind in the interim. Notwithstanding this fact, a significant crust was noticeable about 9 inches below the snow surface, which, though not sufficient to bear the weight of a man, was still perfectly definite in character.

The explanation of its formation seems to be quite straightforward, and to be referable to the presence of the warm sea ice below the snow. The upper surface of the snow necessarily forms a surface of temperature discontinuity, and the heated air containing water vapour rising from the warm sea ice condenses most of its moisture at this position of temperature discontinuity, and forms there a less porous and more coherent

mass. If this explanation be correct, the formation of a crust may take place on the surface, independently of the action of the wind or sun, and conditioned by time alone.

This process appears to be sufficient to account for the inception of a crust at the surface of snow deposited under such conditions of low temperature and absolute calm. The later position of the crust, 9 inches below the surface, is satisfactorily explained by the superposition of later falls of snow, but it is now necessary to account for its subsequent growth under these circumstances. It seems probable that growth will continue if the crust, when covered, has already acquired sufficient coherence to offer a bar to the free passage of water vapour. In this case, since the temperature gradient of the snow mass is largely dependent on the convection currents from the sea ice, the obstruction to the convection currents caused by the crust will cause the latter to remain a surface of temperature discontinuity. The growth of the crust may thus proceed under several inches of snow covering, and this appeared to be the case in the example in question, since the lapse of a fortnight seemed to make a decided difference in the rigidity of the hardened layer.

Confirmatory evidence of this subsequent growth is not lacking from other sources. The faces of many of the glaciers of the Robertson Bay district, and many of the bergs observed in the neighbourhood of Cape Adare and of the Nordenskjöld Ice-Tongue, showed numerous delicate blue lines. These structural details of glaciers will be dealt with in another chapter, but there seems no doubt that, in many cases, the blue lines are former surface crusts initiated in the manner just described, the action continuing for some considerable time after the deposition of fresh layers of snow. It is significant that these lines of blue ice are almost, or completely, absent from the ice of the larger tabular bergs which owe their origin probably to some formation on a scale comparable with the Ross Barrier. These latter are probably formed under conditions where the summer temperature of the air and ice seldom approaches freezing-point, conditions which do not hold good on the smaller valley glaciers which transect the north coast of Victoria Land, and which give rise to the small bergs which here line the coast.

Another striking occurrence which cannot well be explained, except in this manner, was observed on the surface of the Campbell Glacier,* where it is confined between the Northern Foothills and Vegetation Island. Here the surface of the glacier is heaped with drift many feet thick, and trenches dug in the snow proved it to be well stratified, and seamed every few inches with blue bands of clear ice. Though some of these were discontinuous, many persisted as far as the trench was dug. These blue bands ranged up to $\frac{1}{4}$ inch in thickness and were most definite. They appear undoubtedly to denote the position of former surface crusts, and probably represent the surface of the snow during previous summers, or possibly of successive snowfalls. These bands are described more fully in Chapter VII, and are illustrated in Plate XXIV. We have never at any time noticed, in this portion of the Antarctic, the formation of ice on the actual surface of snow, except over sea ice. These layers must, therefore, have

* Map XIV.

grown from submerged hardened surface crusts by some subsequent change such as the one here referred to.

A true ice crust is at times formed on the surface of drifts lying on the sea ice, during periods of very great warmth in the middle of summer. The growth of this ice crust must be facilitated by the action of warm air currents rising from the sea ice, and it is always associated with the presence of an air space below the ice layer. Once the ice layer is formed, however, it will act not only as an obstruction for the moisture from the sea ice, but also as an obstruction to the radiation into space. The action is quite similar to that occurring in a conservatory, and the temperature under the ice covering will probably be several degrees higher than the air above. In these circumstances, it is easily seen that the temperature of the sea ice may rise above its melting-point without reaching a temperature sufficient to melt the covering of snow above. In the warmest days of the summer, it is indeed a common experience to meet crusts of this nature covering parts of the sea ice, while other portions of the surface consist of the normal snow-drifts. It was usually found that pools of water, or of very wet slush, occurred under the ice covering, while the unattacked snow-drifts were still solid and well adapted for sledge travelling. The selective action of the sun in such cases is probably governed by such circumstances as the proportion of rock dust in the different drifts, the age of the drift, and the slope of the surface. The first-mentioned factor is the most important.

Change in Internal Structure of Snow.

The change in the internal structure of snow-drifts with lapse of time is probably the least understood of the modifications to which snow in bulk is subject. The modifications we refer to here take place amongst the individual crystals composing the mass, and their cause must therefore be referred to the properties of such crystals.

It is known that ice crystals belong to the hexagonal system, there being three symmetrical axes 60 degrees apart and at right angles to the optic axis. It is unfortunate that our knowledge of the physical properties of crystals is in general still somewhat meagre, but we do at least know that these properties (such as heat conductivity) are different in the directions of the different crystallographic axes, and it would seem reasonable to refer the changes that do take place inside a mass of snow to such differences.

In the Antarctic (as elsewhere), when a snow-drift or other mass of snow crystals persists for a certain time, a change occurs in the size and shape of the individual crystals, this change (at least within certain limits) being progressively towards an increase in the mean size of the crystal. Broadly speaking, this modification probably takes place by the elimination of those crystals which are of least size, and by the addition of their mass to the larger crystals. The growth is much faster at high temperatures than low. The explanation of this change is attempted in Chapter IV.

This dependence of the rate of change upon the temperature is supported by laboratory experiments,* and from laboratory experiments we also know, at least for temperatures slightly below freezing-point, that the rate of change increases with the pressure applied.† These two facts have given rise to the theory that the growth of certain crystals at the expense of others takes place only when the snow or ice is close to the melting temperature, since the rate of growth at the melting temperature (either at atmospheric pressure or under hydraulic pressure) is undoubtedly quite fast. The supposed mechanism seems to be a progressive melting under pressure where the points of the crystals touch one another, and a flow of the fluid thus produced to other places where the pressure is less. This might afford a reasonable explanation of the cause of the growth of the larger crystals at the expense of the smaller in a mass of snow composed of individual crystals at temperatures near the triple point, for the local pressure per unit area must be greater for the smaller crystals, and therefore a greater amount of melting should take place at their surface. It does not, however, afford any explanation of the fact that crystals do slowly grow in size, even at temperatures well below zero Fahrenheit, where the pressure due to the superincumbent foot or so of snow is utterly insufficient to cause any significant local increase of pressure.

It is to change under these conditions that a great portion of the modifications which Antarctic snow undergoes must be attributed, and the explanation of the observed facts cannot therefore be sought in the formation of water. It seems to us that the only reasonable explanation is to be found in a property analogous to the known high vapour pressure of ice, and the very reasonable assumption that this property differs in the directions of the different crystallographic axes.

Growth of one crystal at the expense of another may take place if there is a difference between the mean vapour pressure over the boundary of the two crystals, and will be in such direction that the crystals of least mean vapour pressure will grow at the expense of the others. The manner in which this change takes place would be exactly analogous to the process when two vessels are in free air connection with one another and contain water at different temperatures, the transference of water vapour being from that vessel with greatest vapour pressure to that with the least. In this case the movement of vapour will be from the hot water to the cold ; in the case of the snow-drift, the larger crystals may grow at the expense of the smaller, while the more delicate feathery forms in which the snow fell originally change into more massive granular or prismatic forms.

The factors upon which these structural changes within a mass of snow depend should be determined in the first place by the temperature; all our observations tend to prove this fact. The change from fine freshly-fallen snow to the more massive varieties occurred in winter as well as in summer, but the change, instead of taking place in the

* T. C. Chamberlin, 'A Contribution to the Theory of Glacial Motion,' p. 193, Decennial Publication, University of Chicago, 1902.

† Hess, 'Die Gletscher,' p. 31 *et seq.* (*See also* Appendix to this Report.)

course of a few days, required weeks for its completion. Even during summer, large differences in the rate of change, depending on the air temperature, were noted. Thus, on the Ferrar Glacier, in the summer of 1910–11 during days with high air temperature, the structure in the drifts changed completely in the course of a couple of days. On the Barrier, however (in the summer of 1911–12), when the temperature was well below freezing-point, many days seemed to be required to show the slightest change in the original snow forms, except in the formation and growth of crystals lying on the surface and exposed to the radiation from the sun.

One point which should be mentioned is that after the warmest days of summer, in places where the temperature may rise (even away from black rock) to freezing-point, the structure of the surface snow is sometimes definitely granular, as is snow in more temperate climates. It seems reasonable to suppose, therefore, that the formation of small rounded ice grains in drifts is due directly to the agency of water—the process of change being by melting rather than by sublimation.

On the other hand, where the temperature does not rise to the melting point, the structure of the constituent ice crystals is quite different. During the summer, drifts have on occasion been seen to be composed of myriads of imperfect crystals which seem to be composed of a number of rods bound together into bundles of length about seven times the total thickness. These were named by us "fascicular crystals" (Plate XXXI). The most striking example of this change was observed on Glacier Tongue in January, 1911, where a drift 8 inches deep was found to be composed wholly of these crystals, the individuals having a length up to 1 inch. At lower temperatures still, as on the sea ice during the course of the winter, the form the crystals seem to take is that of fragments of hexagonal plates, and "turret-form" crystals up to $\frac{1}{4}$ inch in diameter (Plate LII). This seems also to be the form assumed by the snow on the Barrier at a depth of a foot or more after it has persisted for some time.

Pressure also, as we know from laboratory experiments, has a very significant effect on the rate of growth of crystals, but no very definite evidence of this effect has been observed in the Antarctic.

The first change from small snow crystals to more massive forms must, of course, be accompanied by a considerable shrinkage in volume owing to the diminution in the number and volume of the air spaces in the mass. The crystals or granules will therefore "pack" more tightly under their own weight. When closely packed, the erstwhile snow covering is known as *névé*, and it is distinguished from snow only by the size and shape of the grain, so that a rigid statement of the difference between *névé* and snow is difficult to formulate.

The further transformation of the *névé* itself does, however, involve a definite change in condition. In *névé*, ice grains are distinct and separated by air spaces from one another. In the further growth from *névé* to ice (taking place by the same process as the change from snow to *névé*), the air spaces no longer form the boundaries of the crystals, but are included in them in the form of spherical or ellipsoidal bubbles.

One of the most remarkable features of this change from snow through *névé* to ice is the extraordinary effect exerted on the rate of growth when the bottom of the mass of snow is already resting directly upon ice. In such cases, as in the formation of a snow-drift on the surface of a glacier or of fresh-water ice, the rate of growth of the snow crystals is enormously increased, the change taking place progressively upwards at the boundary between the two. This change seems to be due to an actual growth of the upper surface of the ice at the expense of the snow resting upon it, the structure of the ice below being propagated upwards into the original snow layers in such a manner that the original boundary between the two is finally hardly to be detected. In one case on the Ferrar Glacier a shallow snow-drift was found to be entirely changed into 2 inches of solid ice in the short space of two weeks.

Still more striking examples of the same rapid change from snow to ice, where the snow lies directly upon an ice surface, have been observed many times on lake surfaces. It is known that some of the lakes, which have afforded opportunities for watching this process, are completely melted during the course of a normal summer, and it is, therefore, more easy to estimate the amount of growth which has taken place in a single season. On Clear Lake, Cape Royds,* at least 6 inches had been added in this way to the height of certain portions of the surface before Christmas, 1912, and it is probable that this addition was made in the single season 1911–12. At Blue Lake, Cape Royds, and at Sunk Lake, Cape Barne, where melting does not take place for at least several years together, this method of change has, in places, added several feet to the original level of the ice.

Though, in these cases, the change has no doubt been hastened by the higher temperature of the ice below, it seems probable that the growth in the example first quoted has been due to the close proximity of the snow crystals of the drift to the much larger grains in the glacier ice, which as we have seen should grow at their expense.

Another good example of this effect is found on the surface of sea ice covered with snow. Even during the winter this change is effective, and in 1911 it was found that, by September, an inch of ice had already been added to the surface. This increase could be easily recognised from the difference in structure between the granular ice thus formed and the original sea ice with its pronounced fibrous structure. In this case, the determining factors were probably the high temperature of the upper surface of the sea ice and the considerable amount of salt caught up between the crystals composing it. Further, we would expect the rate of growth to depend largely on the thickness of the snow covering, which acts as a heat insulator so that the temperature of the surface of the sea ice largely depends on the depth of the snow overlying it. On this point, however, no observations were secured.

One of the best examples we have noted of the dependence of the growth of the individual grains upon temperature, is furnished by an observation on the Ferrar

* Map V.

Glacier, of the ice in the neighbourhood of a large exposed rock, 4 feet high, shown in Fig. 25. Around this rock had been formed a drift, and already by February, 1911, this drift, with a maximum thickness of 3 feet had been completely transformed into ice, identical in structure and surface marking with the glacier ice in the vicinity. Numerous similar examples on an even larger scale could be quoted from the Priestley Glacier and other glaciers in the Terra Nova Bay area.

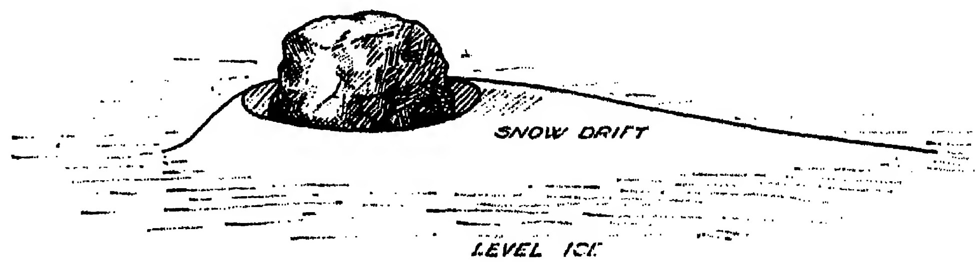


Fig. 25.

Even in a snow-drift before consolidation into ice, the effect of high temperature on the size of the individual crystals is quite noticeable. Thus, in the vicinity of a large boulder on a glacier surface, drifts have many times been seen, in which the separate crystals in the immediate vicinity of the boulder had a mean diameter of almost 1 inch, the mean size of the crystals becoming smaller and smaller as the distance from the boulder increased.

One of the factors in accelerating the change from snow to ice is apparently the degree of packing of the snow while this change is taking place (Plate XXV). The most striking example of this hails from one of the briny lakes at Cape Adare. Here, on the advent of cold weather, the lake froze and was later covered with snow. Penguins, seals, and even men, were constantly traversing the lake, and "packed" the snow surface where they stepped on it. More snow then fell, and for a couple of months the lake remained snow covered, so that no signs of the passage of these various travellers were to be seen on the surface. Finally, however, during the course of the great blizzard of May 4–14, 1911, all this snow covering was blown from the ice surface, leaving the footprints standing out in clear solid ice a full ½ inch above the general lake level—penguin and seal trails, and men's footsteps perfectly outlined in the ice, each after its own kind. This example seems to show quite definitely that the change from snow to ice is accelerated as the result of such pressure.

D

CHAPTER II.

ICE CRYSTALS FORMED FROM VAPOUR.

" And with quite a small expansion—
1·8 or 1·9,
You can get a cloud delightful:
Which explains both snow and rain."*

This little verse, which describes the results of C. T. R. Wilson's† classical experiments on the formation of water drops after expansion of saturated air, will be familiar to all who have carried out research at the Cavendish Laboratory. Wilson's experiments showed that in air, under definite conditions, dust particles or charged ions formed the nuclei upon which condensation of the vapour took place to form water drops. There is no reason to doubt that the same process is effective in the formation of ice crystals by the cooling of saturated air to temperatures below freezing-point. Thus, if there are ice crystals already present in the air, but no dust particles, a decrease in temperature should not cause the formation of new crystals, but should simply induce growth of the existing crystals at the expense of the water vapour. In point of fact, we have every reason to assume that the number of dust particles will be abnormally small over such an ice-covered land, so that, in normal circumstances favouring the deposition of ice vapour, growth will usually take place upon the ice crystals already present in the atmosphere. This assumption may have some bearing on the observed circumstance that all crystals of one type falling at any particular time appear to be of about the same size. It may also help to explain the phenomenon (referred to elsewhere) of the formation of ice crystals on the windward surface of ski, ski sticks, ropes, etc., from an atmosphere which appears to be supersaturated, and to contain water drops at temperatures well below freezing-point.‡

It is known that the equilibrium vapour pressure of a small spherical water drop is greater than the vapour pressure of a plane water surface, the difference being greater the smaller the drop, in the absence of any other source of energy (electrical, for example). An electrically charged drop *can*, however, remain in equilibrium with a plane surface.

Considering first the simple case of a water surface in equilibrium (under given conditions) with its vapour pressure, we recognise that equilibrium demands that the

* Post-prandial Proceedings of the Cavendish Society.

† C. T. R. Wilson, 'Phil. Trans. Roy. Soc.,' A, 192 and 193, 1899.

‡ It is possible, however, that these " drops " are not water, but ice in the non-crystalline " vitreous " form of high potential energy. *See* also footnote to p. 25.

number of molecules entering the water surface must equal the number leaving the surface. If we assume with Todd* that all molecules of vapour which meet the water surface penetrate it, while only those possessing a kinetic energy exceeding a certain amount are able to pass from the liquid to the vapour, we obtain the equation given by Todd :—

$$p = Ase^{-C/R\theta}\left(1 + \frac{C}{R\theta}\right)$$

where p = vapour pressure,

θ = absolute temperature,

R = the gas constant,

C = $\frac{1}{2}$ mV², where V is the velocity of those molecules which are just able to leave the water surface,

s = density of the liquid,

and A is a constant.

In this formula C represents the kinetic energy of a molecule which is just able to escape from the liquid.

(Though the variation of vapour pressure with temperature is fairly closely represented by this formula, it seems more reasonable to suppose that, in reality, only those molecules can escape from the liquid to the vapour which possess a velocity component outwards and at right angles to the surface exceeding a certain limiting velocity.)

The energy change of a molecule on passing the interface liquid-vapour must depend upon the curvature of the surface, the total energy of the mass of liquid being made up of two parts—one proportional to the volume, and the other proportional to the superficial area.

It is necessary to consider an essential difference between crystals and liquids which is of importance in this connection. In liquids the molecules are free to move and are oriented in all directions ; in crystals, the molecules are not free to leave their stations and are all similarly oriented. There is thus the possibility that for crystals in equilibrium with their vapour, all the molecules of vapour striking the crystal may not be able to enter the crystal, but only those which are suitably oriented with reference to the molecules within the crystal.†

In the absence of detailed information regarding the structure of the ice crystal, it does not seem possible to investigate the question from the theoretical stand-

* G. W. Todd and S. P. Owen, 'Phil. Mag.,' vol. 38, November, 1919.

† Volmer and Estermann ('Zeitschrift für Physik,' October, 1921) and Volmer ('Zeit. für Phys.,' March, 1922) discuss this point. The vapour pressures of the different faces of mercury crystals are not sufficiently different to account for the large differences in the rate of growth. Volmer suggests that adsorption takes place of the gaseous molecules on the crystal, and that these molecules possess a certain mobility ; also that the molecules falling on the faces presenting a large surface move on that surface to build up the edges of a plate-like crystal such as mercury. Photographs by Bentley, however ('Month. Weath. Rev.,' November, 1907), of platelike crystals formed in water seem to show that the growth is particularly restricted in those portions of the plates which lie close to an adjacent one, as if there was a poverty of molecules capable of being deposited in the water lying between two adjacent crystals.

point. In practice we know that the form of the ice crystals varies with the physical conditions under which the crystal has grown. Indeed, in the Antarctic, the ice crystals formed within crevasses are, so far as we are aware, always of the same type. Other types are characteristic of other physical conditions under which the crystals have formed, a change in the conditions causing a change in the type. It seems probable that these changes in type are to be referred to differences in the energy change associated with deposition of a molecule on the different faces of the crystal, and its variations with the different physical conditions during growth.

There is no reason, however, to doubt that the same general principles apply in the case of solid-vapour equilibrium as in the case of liquid-vapour equilibrium, the vapour pressure being less over the solid than over the super-cooled liquid at the same temperature. Just as in the case of water drops, the vapour pressure over a perfect ice crystal in equilibrium with its surroundings should be greater the smaller the crystal. Thus, of two such perfect crystals the larger should grow at the expense of the smaller, unless there is some additional source of energy (such as electrical energy) to differentiate the crystals from one another. By a perfect crystal in equilibrium we mean a crystal under such conditions that as many molecules enter as leave the crystal, and also as many molecules enter as leave each face of the crystal. In these conditions the vapour pressure over each face of the crystal must be exactly the same, otherwise growth would take place on one face at the expense of another.

Slight as is our knowledge of the physical properties of crystals, we do know that, generally speaking, the physical properties will be different in the directions of the different axes. Ice belongs to the hexagonal system, and it seems probable that the physical properties along the principal axis will have values differing from those along the three subsidiary axes. The ice crystal has lately been subjected to X-ray analysis,* so the spacing and arrangement of the atoms is now known.

We know by observation that small ice crystals growing upon a large ice crystal are so oriented that the optic axes lie parallel to one another in each ; we do not know whether the forces in the crystal will be sufficiently powerful to change the orientation of the approaching vapour molecule, or whether only those vapour molecules which have orientations lying within certain limits are able to be retained by the crystal. We can, however, feel certain that the vapour pressure over a small crystal is greater than the vapour pressure over a larger crystal of the same type under the same conditions.

Under conditions which are favourable to the growth of a crystal at the expense of the vapour surrounding it, there will be an excess of vapour molecules entering the crystal over those leaving it, the rate of transfer of energy being proportional to the growth. This inward movement of vapour molecules near the crystal will establish a concentration gradient tending to direct molecules towards the crystal faces, and there is the probability that this concentration gradient will be different for the different faces of the crystal.

* Dennison, 'Phys. Rev.,' vol. 17, 1, January, 1921.

Further growth of the crystal will be maintained by this gradient, and, in an enclosed space under identical conditions of temperature, this growth will be largely conditioned by the coefficient of diffusion of the vapour in air.* Under unit concentration gradient, therefore, the mass of vapour passing per unit area towards the crystal will be greater the lower the total pressure and the higher the temperature. The actual concentration gradient, on the other hand, is dependent on the efficacy of the conditions promoting growth of the crystal.

Consider the simple case of a crystal suddenly cooled and kept by some means at a temperature θ_1, below the temperature θ_2 of the vapour and gas surrounding it. If no other condensation nuclei are present in the gas, the whole energy transfer will be to this crystal, whose vapour pressure is p_1 at the temperature θ_1. The vapour pressure corresponding to the temperature θ_2 is p_2, and this depends somewhat upon the atmospheric pressure $(P + p_2)$. The whole difference of vapour pressure between the crystal and the vapour will be $p_2 - p_1$, and the rate of growth of the crystal will be dependent chiefly upon the magnitude of this difference and upon the absolute temperature and total pressure. If means are not provided for maintaining the crystal at the temperature θ_1, the entrance of molecules into the crystal and the consequent transfer of energy will raise the temperature of the crystal and reduce the concentration gradient, the growth of the crystal becoming slower and slower until it finally ceases when $\theta_2 - \theta_1$ became zero.

It should be emphasized that the rate of growth of a crystal will be much greater in a current directed towards the crystal (other things being equal), the rate of growth in this case not being limited to the same extent by the coefficient of diffusion of water vapour in air.

As has already been stated, it is known that ice crystals assume different forms depending upon the circumstances in which they have formed, but it is no easy matter to decide the conditions which cause these differences. Observation certainly shows that, in all cases where the crystal has grown quickly, there is a tendency towards the formation of crystal types with a large ratio of surface to volume, and this suggests that there has been a very large mean transfer of energy during the formation of these types. We may possibly regard the matter this way: The mean energy of the molecule in or on the surface of the crystal is less the lower the absolute temperature; the mean energy of the vapour molecule is greater the higher the absolute temperature; the greater the temperature difference between the two, the quicker is the growth of the crystal, and the greater is the mean transfer of energy per molecule deposited on the crystal. When the conditions favour quick growth, the energy transfer must be large, and this transfer is larger the greater the increase of crystal surface corresponding to the deposition of a given number of molecules. Quick growth will, therefore, favour the formation of types with large surfaces relative to the total number of

* The coefficient of diffusion of one gas in another is inversely proportional to the total pressure of the two gases and roughly proportional to the square of the absolute temperature.

molecules in the crystal, and the types so formed will be crystals of large energy content and high vapour pressure.

An alternative method of viewing the question is as follows: The conditions promoting quick growth are those which demand a large difference between the vapour pressure near the crystal and the vapour pressure at some distance from the crystal, *i.e.*, large concentration gradients. The quickly-growing crystal tends to assume such a form as will most nearly annul this concentration gradient (*i.e.*, a form of high vapour pressure) which will be a form in which the ratio—surface to volume—is large. The tendency in all conditions of growth will be for the crystal to grow in such shape that its vapour pressure will become equal to the pressure of the vapour in the air near the crystal surface. If, now, the mean vapour pressure over a crystal depends not only on the ratio-surface to volume, but also on the ratio of the areas of different crystal faces, an explanation is to hand for the great diversity of form assumed by ice crystals under different physical conditions.

It appears that some such explanation is necessary, in order to account for the fact that ice crystals are so sharply differentiated into plate forms and prism or needle forms; why, in fact, thick plates and short prisms are seldom observed in nature. It is, therefore, suggested that the mean energy transfer per molecule during the growth of a crystal depends upon the crystal face upon which the molecules are deposited. For quick growth there is a tendency to the formation of the plate type of crystal, and for slow growth to the prism type, which may be looked on as the "normal" type of crystal. It is true that the "normal" type appears to be a prism whose length is not less than six times its thickness, and this will have a greater surface than a shorter and broader prism of the same mass. If it is, however, correct that the energy transfer varies according to the face upon which the molecule is deposited, this differentiation may possibly be accounted for.

(1) Previous Observations.

Many investigators have, from early times, made a study of the forms assumed by snow crystals, but little attention was apparently paid until comparatively recent times to the form assumed by ice crystals deposited on objects lying on the earth's surface, or formed in water during the early stages of freezing.

An excellent bibliography of the earlier observations of snow crystals is given in Hellmann's 'Schneekrystalle.'* These observers include Magnus (1555), Descartes (1637), Hooke (1165), F. Martens (1671), William Scoresby (1820), and James Glaisher (1885).

Scoresby classified the various modifications of snow crystals into five main types, and stated his belief that the form of the snow crystals must depend in some manner on the air temperature. Glaisher,† on the contrary, considered that such a relation

* G. Hellmann, 'Schneekrystalle,' Berlin, 1893.

† Glaisher, 'Report of the Council of the British Meteorological Society' (1885).

between crystal form and air temperature was doubtful. Hellmann's observations on snow crystals were assisted by microphotography, and he was able to state that only a small proportion of snow crystals are really symmetrical in form. Hellmann pointed out that, not only prism-shaped crystals, but also hexagonal plates, contained cavities. G. Nordenskjöld, about the same time, showed that certain snow crystals in the form of ice prisms contained both air and water.

The results of Hellmann's observations on the relation between the size and the form of snow crystals were as follows :—

——	Radiating Stars.	Radiating Stars with plate ends.	Plates.
Number of observations	22	10	22
Mean diameter	2·35 mm.	1·57 mm.	1·32 mm.

These figures agreed very well with those calculated from Scoresby's diagrams. Hellmann points out, in this connection, that (other things being equal) roughly the same amount of water vapour is used for both solid and star-shaped crystal forms, so that the plate forms *should* be smaller than the stars.

Hellmann also notes that, in one and the same snowfall, the ratio of length to thickness in prisms is usually constant, and that this ratio is very rarely less than one, but is more commonly five, or even a much larger number.

For the relation between the diameter of snowflakes and the air temperature, Hellmann states that the mean diameter at − 10° C. is only one-third that at − 2° C.

Measurements of microphotographs gave the following results :—

Temperature.	Mean diameter.
− 6° C.	3·4 mm.
− 8° C.	2·2 ,,
− 12° C.	1·2 ,,

These results confirm the earlier statements of Scoresby, Fritsch and Rohrer.

(This result is easily understood, when one considers that the water-vapour content of air decreases with decreasing temperature, and probably explains the occurrence of " diamond dust " in polar regions at very low temperatures. The crystals composing this dust cannot be seen by the naked eye, except by reflected light from the sun.)

In addition, Hellmann gives the following Table showing the relation between temperature and the form of snow crystals :—

Temperature.	Relative Number of Observations of—		
	Radiating Stars.	Radiating Stars with plate ends.	Plates.
	Per cent.	Per cent.	Per cent.
— 6 to — 7·5° C.	52	22	26
— 9 to — 12·5° C.	24	19	57

On the basis of his observations, Hellmann proposed a classification of snow crystals in the following types :—

I. *Plate Form* (O/S usually less than 0·1, where O and S are the amounts of growth along the optic and secondary axes, respectively) :—

(1) Stars (usually at temperatures only a few degrees below freezing-point).

(2) Plates (usually at low temperatures ; crystals smaller than those in I (1)).

(3) Combinations of the two.

II. *Pillar Form* (O/S usually greater than 1 and less than 5) :—

(1) Prisms.

(2) Pyramids.

(3) Combinations of I and II.

(In foggy weather, hail-like forms were also differentiated.)

Hellmann also suggests that the reason crystals in polar regions are not so large as in lower latitudes is, that they are formed closer to the ground, have not far to fall, and therefore have little opportunity to grow to a great size.

The careful observations of A. Dobrowolski* threw much additional light on questions concerning the internal structure of snow and frost crystals, besides confirming, in a general way, Hellmann's relation between the form and the diameter of snowflakes. His observations are summarised as follows :—

Stars without central plate :—

Appendices long	Diameter	3·8	mm.
,, medium	,,	2·0	,,
,, short	,,	1·7	,,
(Mean)	,,	(3·1	,,)
Intermediate forms	,,	1·9	,,
Stars with large central plate and simple plate forms	,,	1·4	,,

* 'La Neige et le Givre.' (Voyage du S.Y. "Belgica.")

For snow of lamellar form only, it appears clear that the flakes of smaller diameter occur at the lower temperatures. The Tables, however, showing the relation between temperature and crystal form give no very definite results. There is, however, some indication from his figures that the ratio $\frac{\text{No. of observations of lamellar forms}}{\text{No. of observations of prism and acicular forms}}$ *increases* as the temperature decreases.

It would also appear that, in the lamellar types, the ratio—number of observations of plates and stars with large plate centres to number of observations of other lamellar types—is greatest at the higher temperatures (3/2, approximately, between + 1° C. and — 5° C., decreasing to 5/6 between — 5° and — 6° C., and to 1/3 between — 10° and — 15° C. Below — 15° C. there were few observations, but the ratio rose again to 1/1).

It would appear from this that, in crystals of the lamellar type, the *solid* forms are more likely to occur at high surface temperatures, the solid prism forms also predominating at high temperatures over the lamellar forms, though it is clear from the observations that *surface* temperature has little to do with the form assumed by the crystal.

A deduction of some importance which has been made from Dobrowolski's observations is that transition forms between the "bayonet" type (prismatic and acicular) and the lamellar type were very rare. In other words, few crystals were observed in which the growth along all axes was nearly equal; either the growth was *chiefly* along the optic axis, or *chiefly* along the secondary axes.

Dobrowolski points out that all types of ice crystal contain air cavities, and that there is a local thickening, in the case of the lamellar type, along the secondaries and their appendices, as well as concentric thickening in the case of solid plates, which probably marks the crystal outline at some stage when its growth was slower. An excellent series of diagrams is given by Dobrowolski, showing how the form of the air cavities in lamellar types is conditioned by the rate of growth of the axes and their auxiliary rays. From these observations, it seems possible that a complete knowledge of the structure of such crystals would enable their life-history to be deduced, if all the various factors upon which the growth of a crystal depends were completely known. As, however, we can have no complete knowledge of the physical conditions under which any snowflake grows during the whole stage of its career, it seems clear that a complete knowledge of the factors governing the growth of a crystal can only be obtained by experimental means in the laboratory.

A number of interesting observations were also made by Dobrowolski on the deposition of hoar-frost (*givre*) upon snowflakes. The chief points of interest established by him were as follows :—

(1) The thickness of deposit varied with the type of snow crystals falling, when different types fell at the same time.

(2) Amorphous forms of frost crystals were most common in foggy weather and at the higher temperatures.

(3) Frost crystals were often unequally distributed, *i.e.* sometimes the plate ends of the arms of a star-shaped crystal were alone covered.

(4) In the case of a granular deposit upon a snowflake, there are several stages apparent in the growth of the crystal :—

(i) With slight deposit—an unequal distribution of frost crystals (see (3)).

(ii) With greater deposit—a thick equal granular deposit of chalky appearance.

(iii) With still greater deposit—a thick heavy plate of vaguely polygonal form.

(iv) In the final stage—a tendency to form in the shape of a pyramid. Thus, the additional deposit took the form of additional layers of less and less area.

In addition to the granular deposit of frost crystals, frost crystals also formed on snowflakes in arborescent and feathery plumes. In both these cases there was often an inclination of the plumes either towards or away from the centre, with a tendency to assume a pyramidal shape, as in the case of granular frost forms.

No definite relation was traced between the form of the frost crystals and the temperature, except that mentioned in (2) above, which suggests that the granular type is due to the presence of water drops.*

W. A. Bentley has also made a close study of the forms of snow crystals,† and has attacked the problem from the meteorological point of view. His results are exceedingly interesting, and are accompanied by many very beautiful photographs of snow crystals, frost crystals, window crystals, and crystals formed in water, which throw considerable light on the method of formation of ice crystals.

As regards snow crystals, Bentley states that the temperature and humidity at the earth's surface have little effect on the form assumed by the crystal, the manner of whose growth he suggests may be due to the state of electrification of the atmosphere.

His general results may be stated as follows :—

(1) There is a difference between the form of snow crystals formed in general and in local storms.

(2) The greater number of, and most perfect, tabular forms predominate in the western and north-western portions of great storms.

(3) There seems to be a general law of distribution of the different forms in other portions of such storms.

(4) This distribution is nearly constant in all storms.

(5) Local storms and low detached clouds usually give frail tabular forms, or the granular type of crystals ; columnar and solid tabular forms are common only to general storms.

* *See* footnote to p. 25.

† W. A. Bentley, 'Monthly Weather Review,' May, 1901 ; August, September, October and November, 1907.

(6) Each cloud stratum, during mild weather (if no other clouds are present), commonly precipitates its own type of snow crystal, as follows :—
   (i) Low detached nimbus deposits large frail branching tabular forms.
   (ii) Intermediate clouds deposit smaller branching tabular forms with solid hexagonal centres.
   (iii) High cirro-stratus clouds, small compact columnar and tabular forms.

Bentley's observations on frost crystals are equally interesting, and are summarised below :—

(1) The great majority of crystals formed over wide areas are of one type.
(2) The columnar type is more common if dew forms first. This is essentially a mild-weather type.
(3) Tabular forms are most common in the winter, and are thought to form on *dry* objects.
(4) On the ground, or ice, the optic axis is usually horizontal, whatever the type of crystal.
(5) When not hampered, the solid crystals are those which grow *slowly*.
(6) Open tabular forms are most common with a rapid fall to a low temperature, or near water.
(7) Hollow funnel-shaped crystals form at moderate temperatures.

The chief results (though sometimes contradictory) obtained by the work of these observers may be summarised as follows :—

(1) Solid forms are due to slow growth ; frail forms to rapid growth of a crystal.
(2) Granular forms of hoar-frost are probably due to water drops.
(3) The size of the tabular forms decreases with temperature, and is less for the solid tabular type than for the frail type.
(4) Transitional forms between the columnar and the tabular types are rare.
(5) There is no clear relation between surface air temperature and the type of crystal.

(2) Observations of Snow Forms in the Antarctic.

No elaborate preparations were made for a detailed study of ice and frost crystals on this Expedition, though a microscope with a small light-tight camera box was taken for photographic work at Cape Evans. The form in which snow was deposited was, however, noted by many of the observers on the various sledging journeys and generally, throughout our stay in the Antarctic, at all stations. During the winters, also, a few microphotographs were taken of frost crystals deposited on various objects and growing in ice caves, crevasses, etc.

Naturally, by far the largest number of observations were made during the summer (and daylight) months, which were also the months when observations were available from more than one locality.

The chief observations were made in the following localities :—

(i) By the observers at Cape Evans (chiefly summer).

(ii) By sledging parties on the Barrier, in the Western Mountains, and on the Polar Plateau (summer).

(iii) By the Ship's Party, near the pack and in open water (summer).

(iv) By the Cape Adare Party (March to December).

By far the greatest diversity of form was noted by the Cape Adare Party and the ship observers, both of these situations being essentially " open-water " stations. In summer, frail lamellar types were very abundant in the pack, the crystals sometimes attaining considerable size with the high vapour pressures prevailing. No general relation between crystal form and temperature could be discovered from the observations on the ship, though it was clear that crystals of all types grew to a greater size with high surface air temperatures. This observation was, indeed, substantiated by the results obtained at all the stations, as well as by the sledging parties, while, equally, no clear relation between temperature and crystal form could at any time be found, with one exception. Snowflakes of frail tabular form were rarely observed, except with comparatively high air temperatures (above 10° F.).

The observations made at Cape Evans and during the sledging journeys were almost entirely confined to the summer months. In these warmer months, star-shaped flakes were most common, and reached their greatest size during high surface temperatures. At temperatures still closer to melting-point, the flakes tended to " pack " or aggregate and fall as clusters of imperfect crystals.

Even on the Barrier, the frail lamellar type was very common, and was characteristic of high temperatures, solid plate and prism forms being generally observed at lower temperatures. No single type was, however, restricted to a definite temperature range. Not uncommonly, crystals of prismatic form were seen with plates attached at one or both ends, the ratio of length to breadth of prism being generally about 6 to 1. Prism forms in which the prisms radiated from a common centre were occasionally seen, but they were more usually separated from one another.

On one occasion, narrow-armed stars were observed to fall, many of which bore, on only one side, a number of auxiliary arms fixed almost at right angles to the plane containing the six chief rays.

Very commonly the weather during which the narrow-armed stars were formed lasted for several days, snow falling in no great amount, but almost continuously, during the period. Stars of this type were observed even as far south as the Beardmore Glacier. It is reasonable to infer from the fact that the crystals grow continuously in this form that conditions demanding quick growth existed from the height where their formation was initiated right down to the ground. Similarly, the more rarely observed star forms

with solid plate centres and " hairy " arms suggests slow growth in the initial stages, followed by quicker growth as the crystal neared the ground, while the superposition of plate ends on the narrow-armed form suggests that the environment of the crystals close to the ground favoured a slower growth than the conditions which existed some distance above the earth's surface. It is unfortunate that observations were not sufficiently numerous to state whether a fall of snow as narrow-armed flakes was preceded by a fall of other types, as might possibly be expected.

On the Barrier, solid plates and prisms* were seldom observed to fall, and even the " fluff-ball " type (Plate XXVI), which was so common at Cape Evans during the winter, was rarely seen during the summer months.

On the western sledge journey in February and March, 1911, the narrow-armed type was not uncommon, but the occurrence of " fluff-ball " snow was relatively more frequent than on the Barrier during November, December and January in the succeeding summer.

On the Polar Plateau, snow crystals in small amount and of very small size were exceedingly common during January, 1912. From notes in the meteorological log of the Polar Party, it would appear that thin clouds were continually forming and being dissipated on or near the surface of the Plateau during this month. These crystals were very small, corresponding to the low temperatures here encountered (mean $-18 \cdot 7°$ F.), and were either in the form of needle-shaped crystals or solid plates.

A point of some interest in this connection relates to the conditions accompanying the appearance of haloes round the sun, due to the presence of ice crystals in the air in sufficient amount to render the halo visible, without obscuring the sun's rays completely. An analysis of the number of occasions on which haloes were noted in the meteorological log during the sledging journeys towards and from the Pole, gives little definite information. On the outward journey haloes were frequently observed on the Barrier, but practically none on the journey up or down the Beardmore Glacier. Many haloes were noted on the Plateau, both on the inward and outward journeys, but chiefly on the far side of the " snow divide,"† where the wind was blowing uphill. Few observations of haloes were recorded on the return Barrier journey of the Polar Party itself, but it is probable that the absence of observations was due rather to the physical exhaustion of the party than to infrequency of the phenomena.

The absence of observations on the Beardmore Glacier is probably real, and argues that conditions on such a glacier may be unfavourable to the formation of crystals capable of causing haloes. On the whole, it seems most probable that haloes are frequently formed over the Barrier whenever the temperature is sufficiently low (*i.e.* between February and November), and on the top of the Plateau at all times of the year; while on glaciers leading down from the Plateau the slope is so great that adiabatic warming of the descending air usually prevents the formation of the crystals to which haloes owe their origin.

* Some of the crystals which were of microscopic size may, however, have been of these types.

† The line marking the highest points of the snow surface.

During the winter months, the most commonly observed type at Cape Evans was that known to us as "fluff-balls," shown in Plate XXVI, and certainly the greatest amount of snow precipitated during the winter at Cape Evans was of this type. Practically all the snow which formed before and during blizzards was of this type, each "flake" probably consisting of an aggregation of multitudes of acicular crystals, Undoubtedly this form was a quickly-growing type, as may be seen on consideration of the circumstances attending its formation.

In the winter months, other forms were observed at Cape Evans, these forms never growing, however, to the dimensions of the "fluff-balls." Examples of these may be seen in Plate XXVII, showing minute plates and prisms which fell upon a glass microscope slide during a spell of cold calm weather when the temperature of the air was falling. On the contrary, the temperature was generally rising during the formation of the "fluff-ball" type.

It was noticeable that no lamellar types other than solid plates were observed to fall in the winter months at Cape Evans, the "fluff-ball" type being apparently the form assumed in the winter by quickly-forming snow crystals, while the minute plates and prisms were those which accompanied the formation of the inverted temperature gradient near the ground.

At low temperatures, and especially upon the Polar Plateau, small crystals could often be seen slowly falling, showing up as minute specks of light reflecting the sun's rays. These crystals were usually invisible to the naked eye, except by reflected light from the sun, though often associated with the simultaneous appearance of haloes. The form of these minute "diamond dust" crystals could not, therefore, be observed, but Dobrowolski states that similar snowfalls were observed by him, and that the crystals (*poudrin*) were in the form of solid plates of microscopic size. He suggests that the reason for their small size is the fact that the crystals were probably formed close to the earth's surface, and had not had time to grow to a greater size.

Numerous observations were made by the Ship's Party on the various journeys in the Ross Sea during the summer and early autumn months. The form of the crystals observed appeared to embrace almost all the combinations which have been figured by previous observers, but the lamellar type (particularly the frail narrow-armed plates) were far the most numerous. The individual crystals were also of greater size than was common at the various shore stations (except Cape Adare), and, at the higher temperatures, the individual crystals tended to join and form even larger aggregates.

One type which seems to have been commonly observed by Dobrowolski grew in the form of a solid pyramid. Only one observation (on board ship) is recorded by us of this type of crystal—a solid truncated pyramid of hexagonal section, which still resembled a lamellar form, but which was definitely granular in character.

By far the most complete observations on snow-crystal forms are those which were made in 1911 at Cape Adare, where conditions were in some measure more favourable to such observations. The series of observations is not, however, for the complete year, and a somewhat different classification into types was used. Thus, the term

"spicular" was used to describe the long needle-shaped crystals and also crystals of size too small to determine the shape.

It is clear that, at Cape Adare, the conditions promoting the formation of snow crystals were somewhat different from those which obtained at other stations. In the first instance, snow fell very frequently in a "granular"* spherical form, throughout the whole period of observation (March to December, 1911). The ratio, number of observations of this type to number of observations of other types, varied, as shown in the Table below (column 2) :—

—	Ratio of number of Granular to other types.	Ratio of number of Granular to Spicular types.	Mean Temperature.	Mean Wind Velocity (miles per hour).
1911—			° F.	
March	0·2	3·0	+18·7	10·3
April	0·8	1·8	+ 9·4	8·4
May	1·8	2·1	— 2·2	9·9
June	0·7	0·7	—14·5	6·0
July	0·2	0·2	—11·9	6·3
August	0·5	0·5	—13·6	6·8
September	0·4	0·4	— 7·5	10·1
October	0·8	0·8	— 0·6	6·6
November	0·8	1·4	+18·5	6·4
December	0·5	1·0	+29·5	8·3

It is certain that in some cases this form of snowfall is due to subsequent deposition upon other types of crystal, and that this deposition often takes the form of minute drops of water such as those which are undoubtedly associated with the formation of "frost smoke" over open sea, or open leads in the ice. In other cases, however, the description given is "granular aggregates of needles," or "granular balls with spikes," showing that this class sometimes included types corresponding fairly closely with the "fluff-ball" type, so commonly observed at Cape Evans during the winter and shown in Plate XXVI. Quite commonly, "granular" snow fell at the same time as "spicular." As mentioned before, "spicular" snow included all types which were too small to be observed, and must therefore have comprised both acicular forms and very small plate forms, if both existed.

As regards the frequency of occurrence of different types, snowfall in the form of aggregated plate forms was observed at Cape Adare only in the warmer months—March, April, November and December—with a single observation in May during an unusually warm period. Solid and star-shaped plate forms were most commonly observed in the same months, but were also noted on two occasions in July and on two in September. Except in the latter two months, the temperature was always

* The term "granular" is used in the same sense as did Dobrowolski, the crystals having an amorphous granular appearance, which is probably due to their formation in an atmosphere containing supercooled water drops. *See* footnote to p. 25.

above + 10° F. when crystals of this type were falling. The observations in July and September were both associated with a considerable and sudden rise in air temperature.

The ratio of the number of observations of " granular " forms to the number of observations of " spicular " forms is also given in the preceding table in column 3. It will be seen that this ratio is lowest in the late winter months, June to October, and highest in the spring, March to May. Generally speaking, therefore, " spicular " snow is relatively more common in the coldest months. From the uncorrected mean temperatures of those days on which the two types were observed, it is found that the mean air temperature of the days when these two types were formed differed very slightly in any one month. The differences, though small, seem significant, for, in each month between March and June, inclusive, the mean temperature so derived for " spicular " snow was slightly lower than the mean temperature during formation of " granular " snow, while the reverse was true of each month from July to December, inclusive.

The deduction is that, with decreasing temperature, " granular " snow falls at a higher temperature than the " spicular " type, and with rising temperature is formed at a lower temperature. Thus, whatever the temperature may be and whether it is rising or falling, on the average, snow is formed in the granular type before it forms in the spicular type.

A study of the detailed observations suggests that this is not the whole story, and there is some evidence that the commencement of a snowstorm at Cape Adare is heralded by the formation of " spicular " snow which later changes to snow of the " granular " type; under appropriate conditions, this type may then give way to the plate-like forms which, at the height of the storm, do not possess solid centres and have very fragile arms; when the storm has passed its zenith, this form gives way to the " granular " type and finally to the " spicular " type. Naturally, the whole sequence is seldom complete; in winter, for instance, the plate type is seldom formed.

It is not proposed to give the observations in detail, but it seems desirable to include the remarks summarising the observations of each month. These are given below :—

March, 1911.—Snow falling on 59 occasions out of 236 observations in all.

There was a tendency towards the end of the month for all types of snow to become smaller in size, while "spicular" snow (needle-shaped crystals) became more common.

April, 1911.—Snow falling on 77 occasions out of 222 observations in all.

Predominance of "granular" snow and commencement of "spicular" snow in large amounts.

Decrease in size of crystals and grains. Comparative frequency of stars with granular centres. Separation of snow from the lower layers of the atmosphere as a frozen " fog," composed of minute particles.

May, 1911.—Snow falling on 69 occasions out of 292 observations in all.

May was marked by a distinct decrease in the amount of snowfall (without a decrease in overcast weather); by a complete absence of definite crystal forms; by the extreme smallness of grain; and by the occurrence of the clots or flecks of snow which mark precipitation during strong wind (fluff-balls) and which are quite distinguishable from drift.

June, 1911.—Snow falling on 31 occasions out of 355 observations in all.

June was marked by a very small snowfall, all of the granular or spicular type.

July, 1911.—Snow falling on 88 occasions out of 369 observations in all.

By far the greatest amount of snow fell as small spicules and granules, but on two occasions star forms were noted. On these occasions, the temperature was unusually high.

On occasion, both with and without wind, snow fell in a fragmentary form resembling drift.

August, 1911.—Snow falling on 51 occasions out of 243 observations in all.

All snow fell in the granular or spicular form.

September, 1911.—Snow falling on 36 occasions out of 193 observations in all.

All snow was of the granular or spicular type, except during the fall of September 14, when the greater part of the snowfall was in the form of narrow-armed stars.

Occasionally the spicules have been very small and aggregated in flecks of 50 or 60 spicules. This type of snow has usually fallen during a breeze of at least moderate strength (fluff-balls).

October, 1911.—Snow falling on 49 occasions out of 161 observations in all.

All snow was of the granular or spicular type. There was an apparent tendency towards an increased size of grain.

November, 1911.—Snow falling on 33 occasions out of 228 observations in all.

An increase of plate forms at the expense of other types. Snowfall for the month has been small, but grains are of larger size.

December, 1911.—Snow falling on 37 occasions out of 248 observations in all.

A small snowfall and characterized by the immaturity of the crystals which fell. On only two or three occasions were ice stars observed.

Rain fell on two occasions.

At Cape Evans, during the winter, it seemed possible to divide the types of snow into two classes:—Those which formed while the air temperature was rising, and those which formed when the air temperature was falling. Apparently the "fluff-ball" type was characteristic of the former conditions and solid plates and prisms characteristic of the latter conditions, the amount of snowfall in the latter case being very small.

If it could be determined with certainty that this was also the case at Cape Adare, the point would be of some importance. Forms in which the ratio of surface to volume

is large we have already associated with a quick rate of growth, probably a mixing of two masses of air with different temperatures and percentage humidities; forms in which this ratio is smaller may be associated with slow cooling (by radiation and by contact with colder solids).

If it is true that frail snow forms are due to quick growth and solid forms to slower growth, we can certainly associate the former types with a larger energy transfer than with the latter types. We would then expect the former to be types characteristic of the snow when the snowstorm was at its height and the latter to be associated with the earlier and later stages of the storm. Whether this reasoning is correct or no, this is indeed true of those Antarctic snowstorms of which we have a fairly complete record. A high air temperature is also associated with the period of maximum snowfall and may have some influence on the type of snow formed, but can hardly be said to be the cause which determines the type which shall be assumed.

Laboratory experiments would throw much light on this vexed question and should lead to results of value to meteorological science.

(3) Frost Crystals.

As it soon became clear that only an immense mass of data would enable any clear deductions to be drawn as to the relation between crystal form and the various physical conditions in the atmosphere corresponding to imperfectly-known conditions on the surface, little further attention was paid to the form of snow crystals. A study of frost crystals formed on the surface under fairly well-known conditions seemed, in fact, to promise much better results, though, even in this case, the physical conditions governing the formation of the frost crystals were far from well known in the majority of cases. Our chief disadvantage was our lack of knowledge regarding the absolute and relative humidity of the air, as it became clear from the first observations, that the rate of formation of the frost crystals had an almost decisive effect upon the form assumed by the crystal.

It will be convenient to examine what types of frost crystals were observed at different times of year under different conditions before proceeding to analyse the results obtained. First of all, however, certain points which govern the whole action of frost-crystal formation must be stated. These are :—

(*a*) Frost crystals which are formed on already existing ice-forms tend to grow in such a manner that the axes of the new crystal form are parallel to the axes in the old form.

(*b*) Other things being equal, the crystals tend to grow towards the direction from which the supply of ice vapour proceeds. Thus, if the crystal is of the lamellar type, the optic axis tends to lie at right angles to the direction of supply of vapour; if the chief growth is along the optic axis, this axis tends to lie parallel to the direction from which supply emanates, but this tendency is much less definite than for crystals of the lamellar type.

From what has been written in the earlier part of this chapter, we are prepared to find that the type of crystal formed is largely dependent upon the rate of growth of that crystal, and to find that the freedom of circulation of air around the crystal, which modifies the concentration gradient of the water vapour, will play an important part in deciding the type of crystals formed.

Let us first consider the types of crystals formed on snow and ice surfaces in the Antarctic during those months when the sun appears above the horizon, 85° south latitude being the southernmost limit for which sufficient observations are to hand.

In the summer, radiation from the sun and sky exceeds radiation from the surface to the sky and other surrounding objects. It is clear, therefore, that many portions of the ice or snow surface will often be at a higher temperature than the air in contact with it, so that, as is indeed the case, we should expect the most likely positions favouring the growth of frost crystals to be those which are partly sheltered from the sun, as in the minor depressions of the snow surface. The sun's rays heat the sun-bathed portions of the snow surface, causing a vapour pressure which is greater than that over the portions of the surface which are shaded from the sun, and inducing growth in these latter places. Our observations in summer (excluding, for the moment, observations on the Barrier and the Beardmore Glacier), may be summarised as under :—

(i) In the vicinity of water, especially at low air temperatures, the feathery (pinnate) form was the most common (Plates XXVIII and XXIX).

(ii) On the lips of small depressions in the surface, the most common form was a solid lamellar type (hexagonal type).

(iii) In more shady positions and in large depressions, solid prismatic forms (fascicular or prismatic type (Plates XXX and XXXI)), were found growing upwards from the bottom.

(iv) A combination of the two latter types (Plate XXXII) was commonly observed in small depressions. This we have every reason to believe was due to alternations in the intensity of the sun's radiation, the plate form growing when the sun was shining most strongly and the prism form when the sun's rays were less strong. This complicated structure was built up by the formation of prisms at the angles of hexagonal plates (and at right angles to the plate), whenever growth became slower; other plates similarly related to the prisms later forming from the free ends of the prisms as soon as growth again became faster. (This form was also occasionally observed in the lobby of the stables (see Plate XLVI).)

(v) During foggy weather, growth took place everywhere on the snow surface, the form being somewhat of the type mentioned in (i) (Plates XXXIII and XXXIV).

(vi) Fascicular crystals as in (iii) were occasionally found lying *lengthwise* on the surface of clear ice, especially during the autumn months. Their occurrence was not common, and they were never present in any great numbers when seen. They sometimes attained a length of 2 inches and a breadth of $\frac{1}{8}$ inch.

All these crystals were observed throughout the summer and at all temperatures and heights. The feathery forms obviously grew in localities and situations where there were large vapour concentration gradients; with smaller gradients, the solid plate forms were found; while, with the smallest gradients, solid prismatic forms were most common. Thus, on many occasions, pinnate forms were found on snow slopes facing north (*i.e.* on the sunny side), while on level snow surfaces the predominant type at the same time was prismatic, and on the lips of small depressions in the level surface solid plate forms were most common.

We have already suggested that the form assumed by frost crystals is chiefly conditioned by factors determining the rate of growth, and it will be seen that (i) to (vi) above substantiate this assumption, with the possible exception of (vi). The formation of these horizontal-lying fascicular crystals on a bare ice surface was not observed on glacier surfaces, but only on bare sea ice, or the ice covering freshwater ponds, and their occurrence is somewhat difficult to explain, though it is possible that the conditions approximate to those which obtain within a snow-drift. It would certainly have been much more surprising to find bare sea ice covered with crystals of a less massive type (of higher vapour pressure). The occurrence of the crystals lying flat on the surface (not projecting from it) is probably an indication that the conditions for the formation in this type only existed very close to the surface of the ice sheet.

When we come to consider the observations made at latitudes above 78° S., on the Barrier and on the Beardmore Glacier, the same general principles can be seen to determine the formation of frost crystals on the snow or ice surface. The only real difference is that combinations of prism and plate forms, as in case (iv), were less often observed. Naturally also, pinnate forms were less frequent than at lower latitudes. The changes which took place on the surface will be better understood after reading the section referring to the form of crystals found in the surface layers of the snow. Generally speaking, however, in conditions when fascicular types were formed on the surface, plate and pinnate forms appeared on the northern side of snow cairns exposed to the full rays of the sun. The pinnate form occurred only rarely, when radiation was particularly intense. In these circumstances, also, hexagonal plate forms growing from the fascicular forms appeared on the Barrier surface, and their formation was coincident with more intense conditions of radiation.

It should be pointed out that, both on the Barrier and elsewhere, when snow is deposited in light feathery flakes, these very quickly change on the surface to other and more stable forms; to massive fascicular, prismatic, or pyramidal types. This quick change can only be referred to the relatively high vapour pressure associated

with ice crystals of the "feathery" type. Commonly also, when snow crystals of the feathery type were falling, the crystals already lying on the surface developed feathery ends.

During the summer months, dark objects are rarely found to serve as the support on which frost crystals grow, owing to the fact that they are normally, owing to absorption of the sun's radiation, at a higher temperature than the air surrounding them. This is not, however, true for a class of quick-growing crystal which we have called "fog-crystal." These form under different circumstances, one of which was typified on the Barrier, the other at Cape Adare. Fog-crystals were quite commonly formed on the Barrier, but particularly in the late summer, the crystals usually, but not always, being deposited both on the snow surface and on such objects as ski, ski-sticks, etc., projecting from the snow. The crystals were of a very feathery type (Plate XXXIII), similar to those deposited at the entrance to the stables (Plate XXXIV); were formed even at low temperatures, and in preponderating amount on the *windward* side of all objects. They were commonly accompanied by a yellow "fog-bow" in the sky (opposite to the sun). For these reasons, it is believed that their occurrence was associated with super-cooled water drops, even at such low temperatures, though this demands an almost total absence of "condensation nuclei" in the air.*

On the Barrier and the Beardmore Glacier, the occurrence of "fog-crystals" was usually associated with a succeeding spell of comparatively warm weather, during which, sometimes for several days, snow fell in small amount in the form of narrow-armed plates. Snow-falls of this type were particularly trying, as the light was always bad, owing to the fact that the light reflected from the surface was on these occasions almost exactly the same as that transmitted from the sky above. Sometimes, for days on end, it was impossible to distinguish the horizon at all, making steering a matter of exceeding difficulty.† These conditions usually obtained when the snow was falling in the form of narrow-armed flakes.

The other type of fog crystal was best developed at Cape Adare during the winter, and at times when moist air was slowly moving over the station from the open water holes and lead. Their occurrence in this case can with greater certainty be ascribed to the presence of water drops in the air, and it seems probable that this class of crystal is identical with Dobrowolski's hoar-frost (*givre*), though the granular type was with us only once observed at any distance from open water.

The preceding remarks refer to frost crystals which grow in the Antarctic when the sun is above the horizon. During the winter, when the sun never rises, conditions are generally quite different and radiation from the snow surface is very great. During these months, conditions unfortunately do not lend themselves to accurate observations on the type of frost crystal, especially as the normal cold-weather crystals are of comparatively small size. Except those formed near open water, the only frost crystals,

* *See* footnote pp. 25 and 50.

† Conditions were often so bad that a large snow cairn 7 feet high could not be distinguished 20 feet away, though a dark object could be seen at a distance of 2 or 3 miles.

formed in the open, which we have been able accurately to observe during the winter, were those which formed and were collected on glass microscope slides exposed for this purpose so as to radiate to the sky. The type of crystal formed *on* the slide was distinctive, but was obviously related in some way to the glass surface. Plates XXXV and XXXVI show some of these "arborescent" forms, together with a few minute crystals which had *fallen* from the sky. The occurrence of these crystals was invariably associated with a falling air temperature, caused by radiation to the sky during calm weather. At the times when crystals formed on the glass slides, ice surfaces also developed a growth of hexagonal plates on the surface, which prolonged the existing axes in each crystal and formed scale-like projections which lay parallel to one another on the surface of each ice grain. Thus, an individual grain on the surface of one of the lakes at Cape Evans and Cape Adare would be seen as a bright patch in the reflected light of the moon (when the eye was suitably placed), a neighbouring crystal appearing dark from this position, but showing up as a bright patch when observed from some other position.

Occasionally in summer, crystals would form on the under-side of ice, which had at one time formed the surface of a glacier stream, but which had since drained away. and these could be seen to lie in a similar manner. The crystals could then clearly be seen to be composed of minute plates similarly oriented on the surface of the same grain, but differing in orientation from grain to grain.

Occasionally during the winter, frost crystals were observed to form in the open on other supports, but, though a good example is shown in Plate XXXVII, it was seldom that the type of crystal could be observed.

It was quite otherwise, however, with the crystals formed in the neighbourhood of open water during the winter, near cracks in the ice and on newly-formed sea ice. Many observations were made on these crystals and the results appear to substantiate our theory. Where quick growth took place, a feathery pinnate type of crystal was observed; when growth proceeded more slowly, more solid lamellar forms were seen; while, not uncommonly, fascicular forms such as those shown in Plate XXXVIII were also observed. In general, the latter type seemed to be characteristic of slow growth. On more than one occasion, pinnate forms appeared close to a lead of open water, solid plate forms a short distance away, and fascicular or prismatic forms at a still greater distance.

One observation of the formation of fascicular crystals on new sea ice deserves further notice. The observation in question was made in April, 1912, during an attempt to relieve the Northern Party. Between Butter Point and the Koettlitz Glacier, a stretch of black sea ice about 10 inches thick was traversed which was thickly carpeted with rosettes of "ice flowers" in the form of nearly upright fascicular crystals up to 4 inches long and $\frac{1}{8}$ inch thick (Plate XXX). There seems no doubt that these crystals were formed during the very cold calm weather which immediately preceded our visit, and it is probable that the rather unusual type of crystal form in these "ice flowers" owed its origin to an entire lack of even the slightest breeze while the sea ice was forming.

As pointed out before, a slight air current must profoundly modify the vapour concentration gradient.

Generally, the frost crystals formed at a low temperature near water are of a pinnate form, due to a large concentration gradient; but in absolutely still air, opportunity is given for the formation of the more solid types of crystal.

The effect of a current of air in modifying the vapour gradient must be considerable, and observations made on crystals over the outer door of the pony stables clearly show that the feathery form of the crystals in this situation is due to the considerable current of warm moist air passing the comparatively cold crystals already present over the entrance to the stables. Other examples of the formation of feathery types in enclosed spaces, due to a large vapour concentration gradient, were observed over the door of the hut and on the ice covering the inner side of the windows, during the enforced stay of the Depôt Parties and the Western Party at Hut Point in April, 1911. The same type is always formed when a block of very cold ice is brought into the warm air inside the hut, feathery crystals $\frac{1}{16}$ inch long forming on the surface of the block of ice in the course of a minute or two.

A considerable number of observations is available on the form of frost crystals observed in the pony stables, and particularly in the lobby which connected with the stables proper through a door (usually kept open), and the outside, through another door which was more usually kept closed. The temperature within the lobby varied, being usually a little below freezing-point near the roof and from 10 to 15° C. below freezing-point near the floor. The chief outflow of moist warm air was close to the roof, and here the frost crystals were almost invariably of lamellar type, the plates pointing inwards (Plates XXXIX, XL, XLI, XLII and XLIII). At a lesser height, more solid forms of crystal predominated, and near the floor prismatic and fascicular types were the most common (Plates XLIV and XLV).

Very commonly, combinations of these two types were seen as figured in Plate XLVI, fascicular or prismatic forms growing at right angles to the plates, sometimes to build up the complicated form which was so frequently observed in the open air in summer (Plate XXXII). Individual spikes growing from a lamellar form are shown in Plate XLVII. The very perfect crystals characteristic of summer growth in the open were very seldom observed under the conditions obtaining in the stables.

A certain number of observations was also made on crystals formed in the pendulum ice cave, which was frequently visited, a considerable amount of moisture (from the observer's breath) being left after each visit. The crystals formed from this vapour were occasionally collected on microscope slides, giving the forms shown in Plates XLVIII, XLIX and L. The temperature of the ice in which the cave was constructed varied from $-18°$ C. to $-25°$ C. in this period. From the form, it is clear that the crystals were formed in the air and later deposited on the slides. On the lower portions of the ice forming the sides of the cave, crystals grew in minute plates with rather thick ribs, these being deposited on each ice grain so as to prolong the existing axes, all being therefore similarly oriented on the surface of each individual grain.

Experiments were at times made in this cave on the freezing of fresh and salt water, and it was found that feathery crystals of the type shown in Plates XXVIII and XXIX were always formed on objects above and close to the freezing water, these crystals growing to a considerable size in a few minutes, especially if the sample of water was originally warm.

In crevasses and in artificial caves which are seldom visited, the frost crystals are restricted to a single type, both in winter and in summer. This type when complete, is of hollow pyramidal form (turret-shaped), comparatively coarse in structure and growing sometimes in enormous clusters. These hollow crystals are very difficult to figure ; the sides often converge to a point, but there is no general rule. In their most perfect form, they resemble a hexagonal plate which has been distorted so that the centre of the plate forms the apex of a hollow pyramid of hexagonal section. More commonly, however, the sides of the pyramid do not close, while the section of the pyramid is very frequently rectangular, as shown in Plate LI. The whole crystal is of a very massive type as might be expected in view of the conditions in which it develops, *i.e.* in an enclosed space with a very small vapour concentration gradient. It is clear that a considerable quantity of air is present in the body of the crystals. In view of the conditions under which they grow, it is possibly strange that even more solid (prismatic) forms are not observed in crevasses ; none were, however, seen.

We should naturally expect that the loose crystals in snow-drifts on the surface would approximate to this form of crystal, in view of the similarity in the conditions of formation. Our observations show that this is indeed the case, except in warm weather, though the crystals are never perfectly developed, having the appearance rather of broken fragments of the perfect pyramidal type. A number of these crystals from the body of a winter snow-drift are shown in Plate LII. In the summer, however, both on the Barrier surface and in lower latitudes, drifts were commonly composed of crystals of the fascicular type, all the observations of this type referring to warm days and to positions near the upper surface.

It has already been mentioned that crystals formed directly on glass plates assume a typical arborescent form, which is probably connected with the structure of the glass itself. These types are well shown in Plates LIII and LIV, the latter of which is a photograph of the crystals formed on the inner side of the outer pane of a double window. On the inner side of the inner pane of a window in a warm moist room the frost figures shown in Plate LV are invariably formed, but their formation appears to be directly due to the presence of water. In this plate, the frost figures are made more apparent by the subsequent deposition of tiny frost crystals on the ice. At higher temperatures frost deposition may take place in a granular form, the deposition in this case probably being from water drops in the air.

Rate of Growth of Frost Crystals in the Free Air.

From the previous remarks, it will be clear that the rate of growth of frost crystals varies enormously according to the physical conditions under which the crystals are formed.

The fastest growing crystal is clearly of the frail pinnate type, and we have often observed crystals $\frac{1}{2}$ inch in length which have been formed in the course of half an hour under favourable conditions.

An interesting experiment is to bring a large piece of ice at $-40°$ C. or F. into a room at about freezing-point. Delicate feathery crystals at once begin to grow on the surface of the ice and in a minute or two are $\frac{1}{16}$ inch long.

Observations on the rate of formation of other types of frost crystals are less complete. Frequent references are, however, made in our notes to the formation of plate ends on the originally pinnate feathery crystals in the course of an hour or so, while considerably greater periods seemed to be necessary for the formation of prismatic or fascicular crystals of similar dimensions.

As regards the rate of change from one type of crystal to another, the observations are very numerous. Naturally, the quickest change is the change from the frail pinnate type of crystal to more massive forms, and snow of the type mentioned quickly changes to more massive forms once it has reached the ground. The reason for this change is the high vapour pressure of the crystals possessing a large surface relative to volume.

Though the changes which take place in the body of a snow surface must obviously be slow, it is clear that at the surface itself the changes in the physical conditions of the air and variations in radiation from the sun will be considerable, and that crystals on the surface will be continually changing in form. On the Barrier sledging journeys it was interesting to note how the surface crystals varied in form from day to day, depending on the air conditions and on the intensity of the sun's radiation. On one day the surface would be carpeted with fascicular crystals, on the next day with coarse plate-like forms, or with large flat plates which reflected the sun's rays, showing up as numerous small areas of white light on the snow surface. Many times it was observed that a few hours' sunlight on the surface caused the growth of crystals which continued, on the snow surface, the 22° halo formed by crystals present in the atmosphere. More often, however, the halo was seen only on the Barrier surface, in the form of a parabola with vertex towards the observer, the individual crystals showing up as very bright spots of light; red, green, blue, and all the colours of the rainbow. Inside the parabola no coloured points of light were to be seen, outside the parabola many very bright coloured specks, decreasing in number, however, as the distance from the parabola increased.

It should be mentioned that the changes in the form of crystals on the Barrier surface may be assisted by the porosity of the Barrier in its upper layers, with consequent movements of air into and out of the mass of snow. It is interesting to note, in this connection, that on one occasion a portion of a 22° halo was observed in a low drift which obviously consisted only of ice crystals caught up by the wind from the Barrier surface.

General Résumé.

The preceding analysis of the conditions governing the growth of various types of crystals, embodies the results of our observations in the Antarctic. Though the observa-

tions greatly lack in definiteness, particularly as to the humidity conditions, the results are sufficient to show that temperature is not the factor which decides the form in which the crystal shall grow, but that the rate of growth is of much greater importance, this being conditioned (chiefly at least) by the vapour concentration gradient, frail types of crystal (*surface*/volume, large) being formed for high gradients, solid types (*surface*/volume, small) for low gradients.

This follows naturally if the mean vapour pressure over frail types of crystal is greater than the mean vapour pressure for the more solid types, but does not exclude the possibility that two crystals of different size and type may have the same mean vapour pressure under identical conditions of temperature, pressure, etc. It is, moreover, difficult to see in what way the rarity of thick plates and short prisms can be explained, except on an assumption that the mean surface energy depends not only on the total surface of the crystal, but also on the relative areas of the different faces.*

There can be little doubt that a detailed laboratory study of the form assumed by ice crystals under determined conditions will yield results of some importance to Meteorology. In this connection, it is important to note that the continued growth of a crystal usually involves the inclusion of a certain amount of air, which gives an insight into the form assumed by the crystal at each stage of its growth. If, therefore, the relation of the crystal form and the included air cavities to the physical factors involved can be established with certainty, a study of the snow forms which fall to the earth's surface should give considerable insight into the physical conditions obtaining in the atmosphere during their formation and subsequent growth. The results of Bentley's observations on the relation between crystal types and the character of the storm to which they owe their origin are full of promise, and suggest that a more detailed study will yield important results.

* Volmer and Estermann ('Zeit. für Physik,' October, 1921) point out that mercury crystals, after reaching a certain stage, stop growing in breadth and increase in thickness.

CHAPTER III.

CRYSTALLINE STRUCTURE OF ICE.

The preceding chapters have dealt with the meteorological conditions promoting the formation of snow, the forms in which this snow is deposited, and the subsequent changes experienced by the snow surface during its change to ice. This chapter deals primarily with the methods of examining the structural changes in ice, the methods of formation and the changes which take place in ice formed from water, and certain details of the structure of glacier ice which have not so far received attention.

Methods of Examining the Structural Changes in Ice.

Methods for studying the form and size of individual ice crystals naturally depend in the first instance on such physical properties of crystals as enable one to distinguish the crystal boundaries.

The first method which we have used for studying the individual crystals in a mass of ice depends on the fact that such a block of ice, exposed to influences promoting ablation, develops on its surface, in course of time, slight depressions at the boundaries between crystals, due to increased evaporation along these boundaries. The cause of this increased evaporation is obscure, but it is difficult to account for the slight troughs so formed in any other way.*

The lines are usually so faintly marked that they cannot be directly photographed and, in order to reproduce their form correctly, steps have to be taken to make them more visible.

One of the best of these methods consists in rubbing the surface of the ice with a soft black-lead or oil pencil. The soft "lead" is deposited in the depressions between the crystals, while on the smooth surface of the crystal itself the pencil leaves no mark. A small expenditure of energy thus leaves the surface with the crystal boundaries well marked. They can then readily be photographed (Plate LVI).

This method is not very applicable to those surfaces, such as frozen sea water, when the ice is so soft that the pressure of the pencil rubs off parts of the surface. In such cases, a useful method of intensifying the marking is by gently rubbing the surface with the finger dipped in some form of liquid ink—barograph ink forms a good medium—and finally rubbing the surface over with a dry cloth. By this process, the ink is removed from the upper portions and left in the depressions between them (Plates LVII and LVIII).

* According to the view outlined in the next chapter, such boundaries must be the seat of molecules of energy-content above the average; the vapour pressure is therefore high in these boundaries.

A better method still, we have found, is to brush the surface lightly with soot carried on a fine camel's-hair brush. This method is not only applicable to all forms of these "reticulation troughs," even where the trough is so narrow that the pencil leaves no mark (Plate LIX), but may also be employed in order to elucidate the structure of certain crystals such as those formed on window panes (Plate LX).

If the boundaries are well marked and the reticulation troughs have in the course of time developed sufficiently in width, they may be made visible by holding a piece of thin paper on the sample of ice and rubbing the surface of it with a soft pencil. The smooth parts are marked by the pencil, while the depressions between the crystals remain blank and enclosed between areas of heavy black. This method, though simple, in that it does not require the help of a camera, cannot be used very generally, as it requires an approximately flat surface and a well-developed reticulation trough (Plate LXI).

If the reticulation trough is well developed, it is quite possible to make casts of the surface by the use of plasticine (Plate LXII). A plaster of Paris cast of the latter can then be made, and in this way the surface can be shown up in its true contours (Plate LXIII).

As a particular development of this are shown two casts (Plates LXIV and LXV), which were made without the intermediary plasticine model by simply pouring the plaster mixture directly on the ice, so that the surface is shown in relief. This method is particularly applicable to the study of the structure of sea ice as in the illustration, the presence of the thin plates of which the crystals are built up being made evident by using a plaster mixture almost at freezing-point. Such a mixture chiefly attacks and melts those parts which contain the most salt, and the spaces formerly occupied by the salty ice, together with those spaces in which the air is concentrated, are filled up by the plaster of Paris. The whole is then left for the ice to melt slowly, and the final result is a very interesting reverse cast. In the photograph, it will be seen that a large number of the ridges corresponding to the freezing planes have been broken off during the melting of the ice.

During the first western geological journey, a study of the structure of different ice forms was made whenever possible by means of a simple polarising instrument constructed after a model kindly lent by R. M. Deeley (Fig. 174). This consisted essentially of a reflecting polariser of patent plate-glass and a Nicol prism used as an analyser. Thin sections of the sample of ice it was desired to investigate were formed by the combined use of a small chisel and a brass plate slightly warmed for the purpose. When the thickness had been

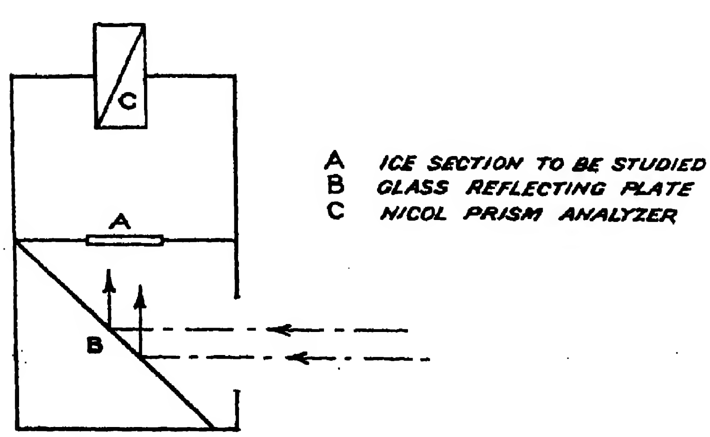


Fig. 174.

reduced to about $\frac{1}{50}$ inch, the sample of ice was inserted between the polariser and the analyser and examined through the latter. As the separate crystals were coloured differently, it was easy to distinguish their boundaries and therefore to sketch the outline of the crystals.

This method is speedy and simple, and is, besides, applicable to nearly every ice form, but it is less satisfactory than the foregoing methods, unless a camera is used. The two cases in which this method fails are :—

(1) When the section comprises a number of separate crystals which have their axes all similarly oriented, so that with a section of uniform thickness the whole field is of a uniform tint; and

(2) When the section, as in the case of sea ice, falls to pieces before it can be reduced to the required thinness.

Another method in which the orientation and size of the crystal may be made evident, is one which cannot readily be induced by artificial means. We refer to the outlining of the crystals by deposition upon them of hoar-frost from the air (Plate LXVI). This method, however, does not lend itself to the process of photography. It was to be observed on the surface of all lakes after a sudden fall of temperature during the winter months, the crystals showing up in the light of the moon as isolated bright patches. The sporadic distribution of these bright patches reflecting the light of the moon was at first sight difficult to explain, since from any particular position only five or six patches could be seen. The general effect was, in fact, similar to that of a number of small, irregularly-shaped mirrors cast down haphazard on an uneven surface. The true cause of the phenomenon was, however, easily recognised when the discovery was made that the shining plates were only visible after a fall in temperature, during which other objects had been covered in hoar-frost. The phenomenon depends on the principle that, when frost crystals are deposited on ice, their axes are arranged parallel to the axes of the original crystals on which they are deposited. Thus, on any one crystal reaching the ice surface, the hoar-frost is deposited in the form of small plates arranged parallel to one another and perpendicular to the optic axis of the crystal. A reflecting surface is thus formed on the crystal at some definite angle to the ice surface. Such a reflecting surface is therefore composed of myriads of small plates which are so small that they cannot be collected for examination, and are usually only rendered visible by the light reflected by them.

On one occasion, however, the phenomenon was developed to better effect, and the actual hoar-frost crystals were of sufficient size to be easily visible to the naked eye. The sample of ice in question was collected from the Koettlitz Glacier on February 23, 1911, and was found on the under surface of ice which had originally formed the surface sheet of a thaw-water stream. By the draining away of the water, the ice covering had been left attached to its banks and sagged towards the centre, so that at the edge a considerable air gap occurred below the ice. The hoar-frost plates were here of quite considerable size ($\frac{1}{16}$ inch in diameter). They could easily be seen to be all standing on

their edges, and, on any one crystal face, they were all disposed as parallel planes. This method of deposition is illustrated in Fig. 33. At the same time, under another portion of the ice sheet, the crystals were seen to be outlined, not in this manner, but by ridges formed of hoar-frost deposited along their boundaries.

A similar result was observed in England in 1922 on Pond-Ice, the light in this case being reflected from small air spaces in the form of hexagonal plates included in the body of the ice sheet. These were less than $\frac{1}{8}$ inch in diameter, and in any one crystal lay parallel to one another. In the majority of crystals these plates were within a few degrees of the horizontal plane. In the case, however, of the long crystals which projected slightly above the general level the planes were lying almost vertical, and these crystals showed blacker than the others when viewed from above. The large bubbles which were the result of decaying vegetable matter were flattened in the horizontal plane, and of circular section in this plane in all crystals.

The final method of determining the size and shape of the crystals is that which has been used by J. Y. Buchanan.* This method depends on the fact that, if an ice block

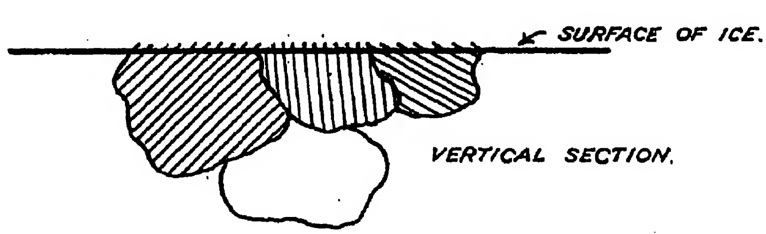
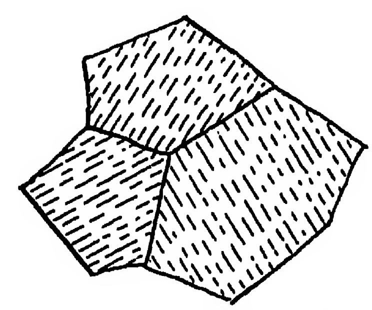


Fig. 33A.—Frost crystals deposited on pond ice.



HORIZONTAL SECTION

Fig. 33B.—Frost crystals deposited on pond ice.

is exposed to solar radiation of sufficient intensity, not only are the boundaries between the crystals outlined by reticulation troughs of greater or less depth and width, but even, in the course of time, the ice mass becomes disarticulated, so that when tapped or shaken it disintegrates into its component crystals. Whether this is due to greater absorption of the radiation at the interfaces, or to the presence of a trace of salt in the boundaries, or, more likely, to the higher mean energy of molecules in the boundaries, is immaterial. It is sufficient that a very valuable method is thus given to us of determining the mean size of the crystals by direct counting and weighing. It suffers from the single disadvantage that the smaller crystals are liable to be overlooked in the process of counting, or destroyed in the process of heating.

In certain cases, the fracture of ice takes place along the crystal boundaries, as in the case of sea and sometimes of lake ice. The best example of such a fracture was seen at the junction of the sea ice with the end of the Ferrar Glacier. Here a small pool of water, which was slightly saline to the taste, had developed an ice covering about 3 inches thick by January 28, 1911. This covering appeared quite black when viewed from above and, to the naked eye, exhibited no traces of structure. On digging a hole

* Paper read before the Royal Institution of Great Britain, May, 1908.

for the collection of water for the cooking-pot, however, the ice covering broke up into a number of vertically arranged cylinders of polygonal cross-section. The number of sides in the polygon varied, but in general there were five or six. The polygons had definitely angular corners, and were on an average $\frac{1}{4}$ inch across. The bounding planes seemed to be accurately vertical and the columns were of constant cross-section.

A similar, but much more striking, case of this polygonal fracture in lake ice was recorded by the Shackleton Expedition from Blue Lake, Cape Royds.* The polygons in this case were rather more than $\frac{1}{2}$ inch across, remarkably uniform in shape, and could be traced to a depth of between 2 and 3 feet, some of them much further. The interfaces between these polygons were most decided planes of weakness, and the ice split more easily along them than in any other direction.

Structure within the Crystal.

In sea ice the structure, owing to concentration of salt and air, is very easily recognised. Not only are the individual crystals outlined, but the crystal is seen to be built up of a number of plates separated by a briny concentrate. This structure is not confined to ice formed from salt water; it may also be recognised in surface ice from ponds and even, under certain conditions, in glacier grains. The planes are well indicated in Plates LVII and LVIII, which represent a sample of sea ice which had been kept slightly below freezing-point for about two weeks, and which had slowly ablated at that temperature, and had then been rubbed with barograph ink. The lines of intersection of the "planes" with the ice surface are the *forelsche streifen* of earlier writers, and obviously they all run parallel in any one crystal. The "planes" are, of course, perpendicular to the optic axis of the crystal. The *forelsche streifen* in a crystal are quite commonly outlined by deposition of hoar-frost, the new crystals being laid down in continuation of the plates, while the spaces between are free from hoar-frost. The direction of the planes—and, therefore, the orientation of the optic axis—is readily recognisable from the structure mentioned above. It is not often in Nature, however, that the appropriate temperature conditions have reigned for a sufficient period of time to emphasise the structure of the ice crystals in this way. We have, therefore, usually to resort to artificial appliances in order to study the compositions of individual grains in detail.

The method most generally used to find the direction of the optic axis in any mass of ice is that which we owe to Tyndall. He discovered that when a beam of sunlight was focussed by a lens and passed through a piece of ice, a great number of small, star-shaped "negative" crystals (Tyndall's figures) were formed inside the mass, and that these lay parallel to one another and perpendicular to the optic axis of the crystal in which they occurred.†

* Nimrod Antarctic Expedition, 1907–9. Geological Report.

† The figures are possibly due to the heating of small dust nuclei and the formation of water about them. The star-like shape may be referred to the differences in conductivity for heat along the different axes of the crystal.

The development of frazil-ice is best studied in swiftly flowing rivers during the winter in such climates as that of Canada. In such situations the surface cooling causes the formation of small plates of ice, while the rapid movement of the water prevents their aggregation into a solid sheet at the surface.

In the Antarctic, the first stage in the formation of sheet ice away from land is the production of myriads of small ice plates in the body of the water. These unattached plates are identical with the "frazil-ice" which forms under the circumstances outlined above. At times these crystals are so numerous that the whole surface is covered with a thick scum, which gives the water quite a greasy appearance (Plate LXVII). Wherever the movement of the water is not too great, the frazil crystals freeze to all objects bathed in the supercooled water, so that by their agency an ice covering may grow with astonishing speed.*

The formation of frazil crystals is naturally not confined to fresh water alone—currents and supercooling may be present also in sea water, and it is to the frazil crystals formed in sea water that most of our observations refer. In sea water, naturally, the amount of supercooling will depend not only on the temperature, but also on the salinity of the sea. Though the actual data for these two are not yet worked out, still our observations show that, for a considerable period of the winter, supercooling (evidenced by the occurrence of frazil crystals) took place to a depth of at least 8 metres below the surface of the sea. During this period (August 5 to October 23, at Cape Evans, 1911) "frazil" was always deposited on the ropes and lines left in the water during the routine work of Marine Biology. The amount of deposit was dependent chiefly on the time the rope was left hanging in the water. Quite commonly, after the lapse of three days, the deposit at the lower surface of the ice reached a thickness of 2½ inches, so that the line here had a total diameter of 5 inches (Plate LXVIII). This deposit tapered off gradually in amount till, at a depth of 8 metres, it was entirely lacking.

At first sight it may appear difficult to understand how it is possible for the frazil crystals to occur at so great a depth, in view of the difference between the density of ice and water. It must be remembered, however, that the crystals are exceedingly fragile, and have a very large ratio of surface to weight, so that the smallest currents and eddies are sufficient to prevent them from rising and depositing themselves on the under surface of the sea ice. In the case of sea water freezing to form an ice sheet, the process of freezing develops a vertical current which will be superposed on any horizontal currents (tidal or otherwise) to which the place is subject. The ice formed

* It should be pointed out that, according to Barnes ('Ice Formation'), the formation of frazil is accompanied by a minute amount of supercooling (1/1000° or so) and, *vice versa*, that supercooling in moving water is accompanied by the formation of frazil crystals. This result seems possible, provided the frazil "crystals" existing are so small that the crystallographic forces are not developed, and the "crystals" can be regarded as a new modification of ice of greater energy than the crystalline form of ice. The best analogy is that of a colloidal solution of ice in sea water. We have also to remember that the melting point of a solid is lower the smaller the dimensions of that particle.

from sea water is much less saline than the water itself, so that the rejected salt forms a solution of greater density which sinks and causes a downward current of small velocity. Though this velocity is small, it is probably sufficient to account for the observed facts. An analogous (but reversed) action in the summer may assist to fill the lower parts of the sea ice and pack ice with diatoms carried from below, a process which takes place to such an extent as to give to much of the ice in the pack a most distinct yellowish tinge.

Frazil crystals appear on the surface of the Antarctic seas generally towards the end of March, and this is directly due to the fall in air temperature about that time. The earliest date, within our experience, of their occurrence below ice of any thickness is recorded from Cape Adare. Here, towards the end of April, trenches dug through the sea ice proved the existence of loose spongy masses of these frazil crystals beneath the flatter pans of the pressure ice around Cape Adare. These deposits were from 2 to 3 feet thick. In fact, in some places they were notably thicker than the ice beneath which they occurred. An example of the occurrence of frazil crystals in the shallow pools of the Cape Adare ice-foot some weeks earlier than this is figured in Plate LXIX, where the crystals are seen attached to the branches of a piece of seaweed.

Mention has already been made of the downward currents of water of greater salinity occurring beneath an ice sheet in process of formation. In addition to this, it is necessary to remember that the passage of a swift current, such as sweeps past Cape Adare under the bottom of the heavy hummocked pack filling the entrance to Robertson Bay, will give rise to a number of vertically disposed eddies which will be quite sufficient to carry such fragile objects as frazil crystals for some distance beneath the surface. We have no record from Cape Adare of these frazil crystals becoming attached to objects such as dredging-ropes, but this is explained by the fact that no dredging by the endless-line method was carried out at this station.

The attachment of frazil crystals to dredging-ropes, etc., has been frequently observed in the neighbourhood of McMurdo Sound, but it is of interest to record that the phenomenon did not take place at Cape Evans until late in the winter of 1911 and 1912. If growth is to continue after the attachment of the crystals—as it undoubtedly does—supercooling* must take place to considerable depths, since conduction along the rope cannot have had appreciable effect at a depth of 8 metres. What then is the cause of sufficient cooling to cause the formation of the crystals? It is within the bounds of possibility that conduction through the ice covering may have lowered the temperature of the water sufficiently, but, from the suddenness with which the formation of frazil ice begins towards the close of the winter, we are led to believe that here the effect may be due largely to the tapping of some other reservoir of cold by the inception of a colder current, or perhaps a current of different salinity. That such a current change can take place is shown by the change in current direction in summer, which plays so large a part in the melting of the Fast-Ice in the same locality.

* The ice bodies which are present in the water are presumably too small to act as nuclei for further growth in size. *See* footnote to p. 80.

Mention is made elsewhere of the fact that the rate of growth of the sea ice at Cape Evans appears to remain constant after the sheet reaches a thickness of about 3 feet. From theoretical considerations, as well as by comparison with the rate of growth observed elsewhere,* it is clear that growth, if due to conduction through the ice covering alone, must become much slower as the depth of ice increases. The constant rate of growth of the sea ice here in the latter part of the winter is therefore strong evidence in favour of the inception of a cold ocean current at that season of the year.

It is from the scum of frazil crystals floating on the surface of the sea that the first layer of sea ice is normally formed. That the succeeding growth is also partly due to the deposition of freely floating frazil crystals seems certain, on consideration of the form assumed by the under surface of the ice sheet. As will be described later, the normal growth is such as to leave spaces on the under surface of the sea ice. These spaces form quiet " havens " in which frazil crystals can deposit undisturbed, but so loosely do the latter cohere that usually the process of lifting a block of ice from the sea-water is sufficient to shake off all those crystals which have not become incorporated in the ice. A more striking example still of this method of growth is furnished by observations in the pack-ice off Cape Adare, during the winter of 1911. Here the pack had been subjected to considerable pressure, and was composed of numbers of pans of widely different thickness frozen firmly together. The bottom of the ice was therefore very irregular, and the underside of the thin pans were somewhat sheltered from ocean currents and furnished areas for excessive deposition of frazil crystals. The deposit of frazil crystals under the thinner pans here reached a thickness of 3 feet in extreme cases.

The structure of the frazil crystals formed quietly on the surface of sea water is quite visible to the naked eye. They are usually squarish in shape and $\frac{3}{8}$ to $\frac{1}{2}$ inch across, though in extreme cases they may have a diameter of as much as 1 inch. The marking of the individual plates is that shown in Fig. 29, which represents a drawing made in December, 1910, on the first south-bound voyage of the " Terra Nova." The optic axis of the crystal is perpendicular to the plane of the plate. Once the frazil crystal has been deposited on some foreign object such as a rope, however, it seems to lose its distinctive marking. This is probably due to the fact that those plates which are sufficiently robust to survive the shaking attendant upon the lifting of the line, have a thickness measured, not in thousandths, but in hundredths of an inch, so that the original marking is quite obscured. Plate LXX shows a photo of a few of the crystals taken from the line shown in Plate LXVIII. Before this photograph was taken, the crystals were exposed to the air in the lobby of the hut until the structure had been emphasised by the deposition of small prism-shaped hoar-frost crystals along the edges of the plates. The arrangement of the individual crystals would apparently be quite haphazard, but for the fact that the floating plates tend to attach themselves to foreign bodies by one of their edges.

* L. V. King, 'Report of the Department of Marine and Fisheries,' Canada.

Anchor-Ice.

Quite commonly in the early part of the winter, before the sun has quite disappeared and while the sea is still free from ice, one can see from the seaward edge of the icefoot that the water is full of fine frazil crystals showing up as glancing points of light. Usually, at the same time, masses of "anchor-ice" up to about 2 feet in diameter can be seen attached to the sea bottom. These masses usually grow on projecting rocks or other protuberances, and are of a light grey colour which affords a distinct contrast to the dark volcanic rock which forms the sea bottom at both of our winter stations. We have noted "anchor-ice" of this kind to a depth of about 3 fathoms, so plentifully distributed as to cover almost the whole of the sea bottom at that depth (Fig. 26). These greyish masses are very easily dislodged by stirring with a bamboo pole, when they promptly disintegrate and rise to the surface as a mass composed of frazil crystals half an inch or so in diameter. The structure derives its name from the fact that the ice appears to be anchored to the bottom. In the rivers in Canada and other northern countries, the masses grow to such a size that their buoyancy becomes sufficient to

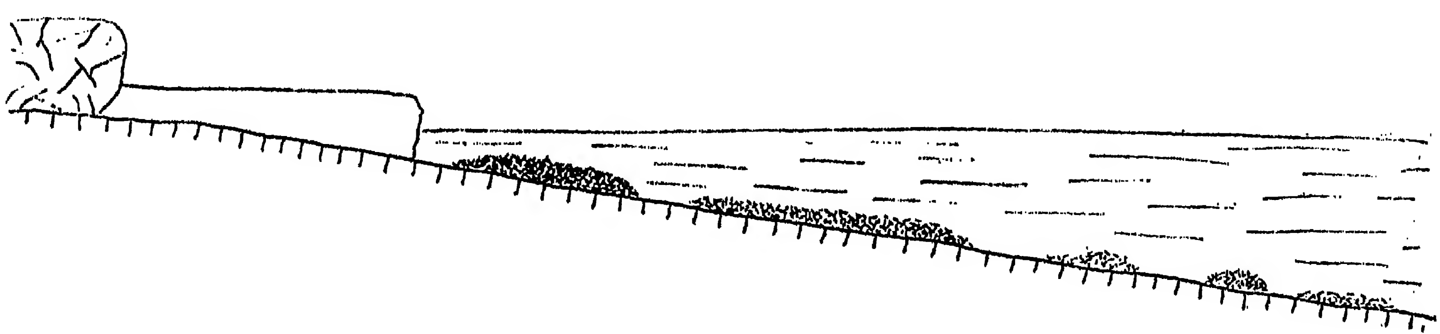


Fig. 26.

raise the large stones and boulders upon which they have grown. This, it is stated, occurs* during warm and cloudy weather when radiation to the sky is least intense. With us, the masses of anchor ice were only seen to rise on one occasion, which was, certainly, a cloudy day.

Of great interest is the fact that the structure of the masses of anchor-ice observed by us in the sea seems quite dissimilar to that observed by Barnes in the rivers of Canada. Thus his description runs :—

> "The growth of anchor ice is exceedingly beautiful, taking place in arborescent forms and resembling bushy weeds. So hard and thick does it become that it is often very difficult to thrust a sounding rod through it. It is very granular in structure, as is shown by an examination of the masses which rise to the surface. Through clear water, the ice looks weed-like, with long tentacles rising up out of the mass."

In South Victoria Land, on the other hand, the masses were always so loosely coherent and so similar in structure to the frazil deposited on the tow-net lines, as to leave no doubt that they were formed in an exactly similar manner. A further point of

* Barnes, 'Ice Formation,' p. 206.

distinction between the anchor-ice observed by Barnes and that observed by ourselves is connected with the manner and time of its formation. Thus, the statement is made by Barnes that anchor ice is formed only on clear cold nights, and this leads to his deduction that radiation is the prime cause for the formation of this structure.

On the other hand, the growth of the anchor-ice we have noticed in the Antarctic seems to be absolutely independent of the nebulosity of the sky, and further to be independent of the colour and constitution of the object on which the growth takes place. With the idea of testing this, various objects of different colours were thrown haphazard into the water. No difference at all between the amount of growth on the light and dark objects could be detected, and it seems certain that any effect of radiation is here completely masked by the much larger supercooling of the water due to other causes. Amongst the objects thrown into the water was a bright tin pail containing a bundle of black iron wire. When this was drawn up again from a depth of 6 feet after twenty-four hours' immersion, and the water carefully emptied out, the structures depicted in Plate LXXI were found. It will be seen that the deposit has exactly the form of frazil ice, and that the crystals have formed on the bucket and on the iron wire in about equal amount.

The single instance we have observed which approximated to the type described by Barnes was seen along a very slightly sloping beach between high and low watermark at Cape Adare, which was alternately exposed to the sea and to the air.

Here, a complete coating of ice was given to the boulders of the beach during absolutely calm weather, and Plate LXXII shows the structure of the ice. The first sign of growth was seen when the boulders were well submerged by the sea water, and it took the form of small rosettes of crystals which were roughly prismatic with pyramid tops to the prisms. In general dimensions, these were larger and a good deal thicker than frazil crystals.

The prisms in fact were very stout and short, and when the boulders were completely covered, by the spreading of the rosettes of crystals until they had merged into one another, the general texture of the ice was distinctly granular in appearance. After the boulders had become completely covered, the addition seemed to be by concentric layers of ice. This ice was quite hard and would have agreed very well with Barnes' description of anchor ice, with the exception that in outward appearance it was quite smooth. Its growth in this form is, however, clearly related to the alternate exposure to water and air, as the tide rose and fell.

With the exception possibly of isolated cases such as the above, it would seem that the formation of anchor-ice of the type formed in the Canadian rivers is unknown in Antarctica.

The masses of "pseudo-anchor-ice" which we have described above, quite evidently grow equally well whether the sea is free from ice or covered with ice, for they have been observed immediately small pools or holes have been developed by tidal action. Radiation cannot, therefore, be the main cause of their formation. Their attachment

to the rocks, however, shows that radiation and conduction may not be inoperative, though the combined result of the two is small compared with the effect due to supercooling as a result of other causes.

The Formation and Structure of Sea Ice.

The frazil crystals which are formed in the sea collect during calm weather to form a thin scum on the surface, the plates lying horizontal. This felt-like mass grows thicker and thicker, if the air temperature is sufficiently low and the sea sufficiently calm, but has at first little rigidity and is readily dispersed by wind. Clearly, this lack of rigidity is associated with the salt solution remaining between the crystals, since it is only at very low temperatures that the whole of this brine can freeze. Owing to heat conduction from the sea below, the cryohydric temperature cannot be reached and all the brine in the upper layers be solidified, until the ice thickness is considerable. As explained in Chapter X, the earlier formed sheets of sea ice are frequently driven out by the autumn gales. The new ice subsequently formed under the influence of the colder temperatures of the winter hardens to a rigid sheet much more rapidly than that formed earlier in the year.

While the above is the normal method of formation of sea ice on the open sea, growth frequently takes place outwards from a bank already consisting of ice formed of irregularly oriented grains, and here the tendency for the new crystals to place their axes parallel to the axes of the existing grains has to be considered. In this case, the course which affairs will take can hardly be predicted. The result will depend largely on the relative amount of heat conducted to the ice at the side, and to the air, respectively, while the former of these will depend on the height to which the ice bank reaches above the water, and on the temperature of the ice. It will be safe to state that, in ice formed under such conditions, the orientation of the crystals will be very irregular.

Another point that has also to be considered in this connection is the instability of the normal flat crystal in water, owing to the lesser density of the ice composing it. Since the crystal formed from water usually takes a plate form, or at least a form in which the optic axis is developed but little in comparison with the axes at right angles to it, it is clear that such crystals standing " edge on " in the water are in a position of unstable equilibrium, and that the only position of stable equilibrium is where they are floating horizontally on the surface. Where, therefore, the first formed crystals are not attached to some object, but float freely on the surface, the orientation of the crystals must be with the optic axis vertical. It is also clear that, even if the first formed crystals are attached to an existing ice sheet, and lie with their optic axes parallel to the surface, the presence of the very slightest amount of swell may be sufficient to detach them and permit them to float in equilibrium. It will, therefore, only be in the calmest weather or in narrow cracks and leads that the *surface ice* will be formed of crystals having their optic axes horizontal.

Though single-plate crystals are in unstable equilibrium if floating " edge on " in the water, it is easy to imagine combinations of plate crystals which are in stable equilibrium when floating vertically upright. The most common arrangement of such individual plates is that shown in Fig. 27, that is, of " A " form in horizontal section.

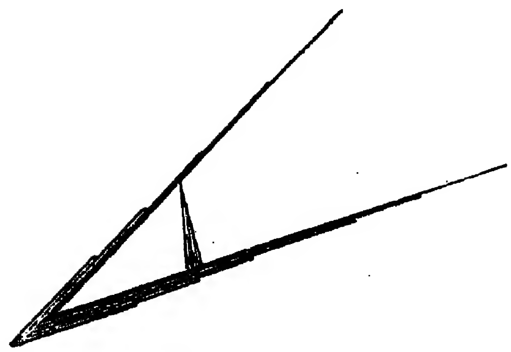


Fig. 27.—Frazil crystals of " A " shape.

Another factor modifying crystal structure in sea ice will be furnished by the precipitation of a certain amount of snow or snow-drift on the surface of the water as it begins to freeze. This snow may be already in the form of plates, but more commonly will not. In any case, it is certain to complicate further the structure of the top layer of ice.

With the idea of gaining more insight into the method of growth of ice, a number of samples of water, both fresh and salt, were frozen in small tin and glass dishes, and the process of ice formation observed as closely as possible. In these experiments, the samples of water were exposed under slightly different conditions in the pendulum cave, where the temperature varied from $-18°$ to $-25°$ C. During the periods of freezing the samples remained quite undisturbed.

The first experiment was made on sea water enclosed in a deep covered tin, so that the cooling surface was formed by the shell of the tin rather than the water surface. The process of formation of the ice could not be watched in this case. In the course of two hours, the water surface had become covered with a soft felt-like mass 1 inch thick, formed of plates about 1 inch diameter, of roughly pinnate or fan-shaped form. The greater number of these rested horizontally, but a certain number stood upright in the mass. These crystals had a thickness of about $\frac{1}{16}$ inch, and were up to $1\frac{1}{2}$ inches long. From the conditions under which their formation took place, it is clear that this surface covering must have been formed largely from flat crystals, which either separated out in the mass of the water, or were detached from the side to float upwards and lie horizontally on the surface.

When, in subsequent experiments, the sea water was contained in a wide, shallow, and uncovered tin dish, the actual process of growth was easily watched (Plate LXXIII). In this case, the first crystals of ice appeared very suddenly on the bottom of the dish by the formation of radiating fan-shaped forms (Plate LXXIV), similar in shape to those observed on the inner surface of an inner glass window pane (see Plate LX). The next step was the formation of ice needles on the upper surface of the water, these growing outwards from the walls of the dish. These first surface crystals looked from above like long thin needles shooting out towards the centre of the pan. The apparently needle-shaped crystals then grew downwards very quickly, first along the side of the pan and then outwards from the nucleus of ice thus formed and downwards from the surface, so that in a very short time a long thin plate was formed. These

plates had a depth of $\frac{1}{2}$ inch, and stood perpendicular to the surface, as shown in Fig. 28. Simultaneously with this growth, the spaces between the long crystals were being filled in by flat crystals lying parallel to the surface. In the course of time these grew to a length of $\frac{3}{4}$ inch, and became underlaid by other similar plates. Though the greater number of the vertical plates started from the edge of the pan and grew inwards roughly towards the centre, still there were a large number of quite detached ones standing in the midst of the mass of smaller horizontal plates, while occasionally they could be seen growing outwards at angles approaching 90 degrees from earlier formed vertical plates. By the time the thickness of the horizontal plates had reached about $\frac{1}{8}$ inch, the vertical-lying plates had reached a depth of 1 inch. If the pan was disturbed at this stage, the felted surface moved easily in waves with a motion similar to that which would be produced in water itself.

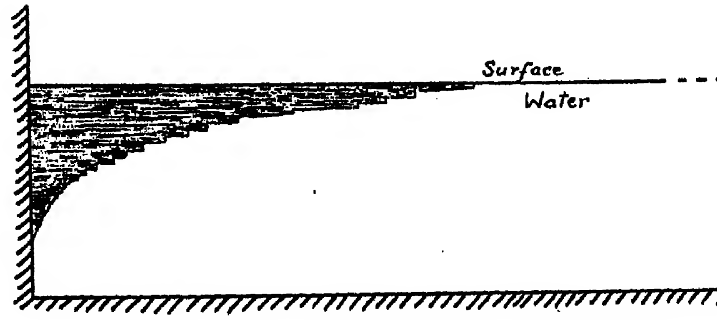


Fig. 28.—Growth of ice crystals from walls of pan containing freezing water.

The extreme flexibility of the ice sheet formed from sea water is due to the mother liquor of concentrated salt solution, entangled between the crystals which are themselves fresh. This still remains liquid even at a very low temperature, so that the individual crystals remain separated from one another by films of brine solution.

When the water in the flat pans is fresh, the method of formation seems to be exactly analogous, and the only difference—except in the degree of rigidity of the covering—is that the individual crystals appear to be slightly smaller than in the case of sea water.

It is unfortunate that the opportunity was not taken of studying the manner of formation under less rigorous temperature conditions. In the pendulum cave, with the small vessels at our disposal, the freezing proceeded at such a rate as to prevent a proper study of the actual formation of the individual plates. Fig. 29 shows a drawing of one of the single freely-floating plates formed in a wooden bucket of sea water at an air temperature but slightly below freezing-point.

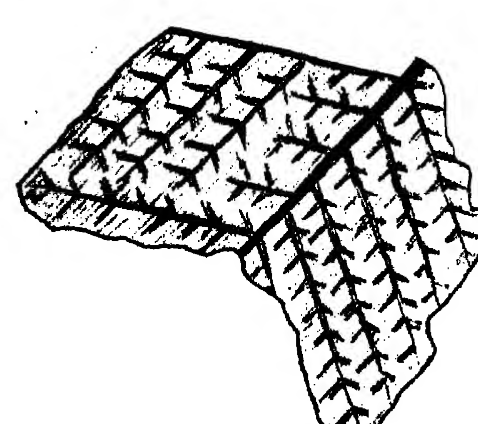


Fig. 29.—Structure of frazil crystal.

The reason the individual crystals can be distinguished from one another during the process of growth is due partly to total reflection of the incident light at the boundary between ice and water, and partly to the greater transparency of crystals in directions perpendicular to the optic axis.

One of the most striking features of the upper surface of ice formed in this way is its irregularity. The surface is elevated over the thin vertical plates by an amount which is probably

only about $\frac{1}{64}$ inch, but which is quite sufficient to be detected in reflected light. Attempts were made to record the form of these crystals by taking a rubbing, but the changes of slope were so gradual that our efforts were only partly successful (Plate LXXV). It would seem, in fact, as if the surface irregularities were due to subsequent changes, such as the different expansion coefficients in the different axial directions of the completed crystal, though possibly the freezing of the cryohydrates enmeshed between the crystals may have contributed to the result.

From what has been seen of the method of growth of the crystals at the time of first formation, it is clear that all contiguous individual plates having optic axes pointing in the same direction cohere to form one crystal grain. The completed crystal grain may, therefore, be regarded as formed of a great number of parallel plates of ice. These are separated from one another by saline solution, if formed from sea water, while the large crystal grains are again separated from one another by a still larger amount of brine.

Our observations on the mode of first formation of sea ice are in general agreement with those made on the mode of formation from sea water frozen in small dishes. Observations on the freezing sea can, however, only be made under certain favourable conditions, and the mode of formation of the ice must be partly inferred from its subsequently observed structure.

The case of sea ice forming in a crack, such as is caused by contraction of the ice sheet on the advent of low temperature, is particularly interesting. Here, the ice at the boundary of the crack is cold. The crystals, therefore, commence to grow outward from each side of the crack along the water surface, in the form of long, vertical-lying plates which may meet in the centre from the opposite sides of the crack, if the latter is sufficiently narrow. These thicken and deepen, and take a roughly triangular form, while at the same time the spaces between become filled with the smaller horizontally-lying crystals (Fig. 30). Owing to the difference in transparency along different axes, the portions formed in the latter way are a whitish colour, while the former crystals, fan-shaped in section, show the same black colour as the sea below. The photograph shown in Plate LXXVI illustrates admirably the difference in transparency of the different crystals.* Quite commonly, the triangular black plates on the surface reach a length of 6 or 8 inches, and have a width of 3 or 4 inches at the base of the triangle.

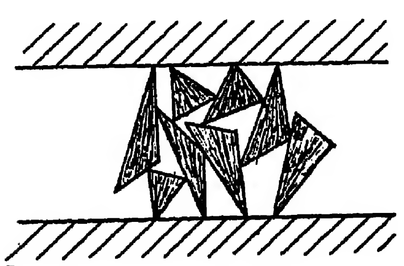


Fig. 30.—Horizontal section of a type of sea ice.

In certain cases, a similar structure may occur far from land, and of this a good example was seen in the bay between Hut Point and Cape Armitage when it froze over in March, 1911. Here the surface of the sea was mottled with small patches of alternately light and dark ice 1 inch to 7 or 8 inches long, very often of the same wedge shape as seen in ice formed in narrow leads. That they are formed in somewhat the same way can hardly be doubted, since whole stretches some square yards in area

* Possibly due to the inclusion of air or cryohydrates between the plates.

frequently occur where the wedge shape is developed almost exactly as in Plate LXXVI. In general, however, the wedges are not so well defined and are smaller in size.

From the meteorological notes made at Hut Point (March 22) during the period of formation of this ice, it seems clear that the ice formed in fairly cold calm weather without disturbance from wind or swell, and was therefore formed under conditions somewhat analogous to those which obtain during the formation of ice on open leads. When, on the other hand, a slight wind or swell, possibly with falling snow or drift, occurs at the time of formation of the ice, the crystals are not able to remain in a vertical position. In this case, the upper portion of the ice is built up of horizontal plates with all optic axes vertical. This surface layer may have a thickness of 1 or 2 inches, but further growth from below is by the addition of vertically-lying plates, the interspaces between these being filled with horizontal-lying plates as in Fig. 31.

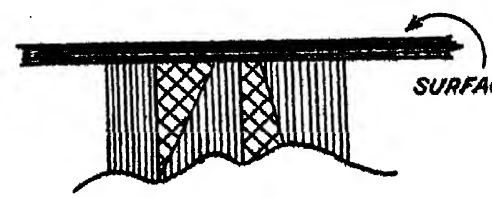


Fig. 31.—Vertical section of sea ice.

That the growth of the sea ice even at a depth of 8 feet proceeds in the same way is shown both by the structure of the ice at this depth, and by the occurrence of the form shown in Plate LXXVII on the under side of the ice. Between the projections shown in the photograph, which take the form of blades, there were originally a few loose crystals, but so loosely packed were these that they fell out when the ice block was removed from the sea.* On examination, all the projecting blades were seen to have their optic axes lying approximately horizontal. These blades may be traced upwards several inches into the mass by reason of their greater transparency.

It is the occurrence of the wedges formed of numbers of plates lying vertically that gives to the sea ice its characteristic fibrous structure, since the wedges, though generally small and not necessarily of uniform section, have a much greater depth than width. The sheet, though described as fibrous, is not formed of bundles of rods, but of bundles of plates of roughly quadrilateral form and with sides of unequal size. The disproportionality in length between the different sides of the quadrilaterals is often as much as ten to one, the sides of greater length being vertical. An examination in vertical section of the upper 4 inches of the usual type of sea ice, shows, in fact, that the upper portion, $\frac{1}{2}$ inch or so, is also fibrous if the term is used in its former sense. The fibres are here plates arranged horizontally, and therefore perpendicular to the plates below. The latter structure is continued down to the greatest depth the ice attains in Antarctic latitudes (Figs. 32A and 32B, Plates LVII, LVIII, LXIV and LXV).

One of the most striking features in connection with the formation of sea ice under normal conditions, is the large amount of foreign matter which is entangled between the large crystals, as well as between the individual plates of which these crystals are formed. This foreign matter consists of dissolved salt present in the sea water, and also air which was dissolved in the water. It is owing to the concentration of these two

* A few of the blades have been broken off in order to gain sufficient contrast for the photograph.

types of foreign material between the crystals that one is so well able to see the structure of the ice. The vertical streams and planes of bubbles, in particular, emphasize the fibrous structure peculiar to this form of ice.

The occurrence of the salt included between the planes and along the crystal boundaries is also of peculiar help in the study of the structure, for, as already pointed out, the presence of salt lowers the temperature at which the ice is able to melt. If a block of sea ice is therefore kept at a temperature above the cryohydric temperature of the sodium chloride which is the chief saline constituent of sea water, the salt cannot now remain in the solid phase, and is therefore able to drain slowly away. As the result of this action, the crystals become separated from one another, and, after a time dependent upon the size of the sample and on the temperature to which it has been exposed, the block of ice may become so loosely coherent as to crumble into its constituent fibrous crystals when touched.

It is no doubt also the local concentration of the salt in vertical planes that gives to sea ice its peculiar fracture. Even at the lowest temperatures the fracture takes place in a vertical plane, so that a simple method is at once available for finding the direction of the plane of flotation at the time of formation of the ice.

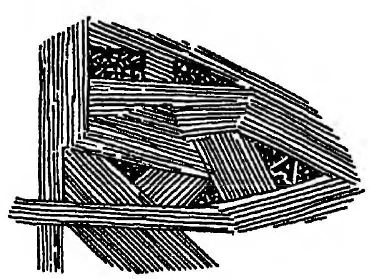


Fig. 32A.—Fibrous structure of sea ice—Horizontal Section.

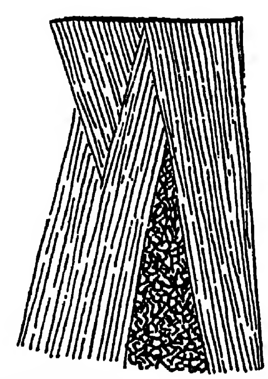


Fig. 32B.—Fibrous structure of sea ice—Vertical Section.

Of the changes in structure experienced by sea ice after its first formation we know little, and certainly no distinctive difference could be noted in the structure of samples taken from the same depth at different periods of the winter. The greatest changes seem to be surface ones, due partly no doubt to a wandering of the excess salt originally in the upper layers, but more especially to a transformation of the lower portion of the snow covering into ice.

Even when the sea ice begins to melt, the structure of the ice in the first stages does not apparently change greatly. Owing, however, to the higher temperature, it is much more "rotten" than it is even on its first formation, and the constituent vertical fibres are able to move almost independently of one another. Thus it happens that sea ice just before its disappearance is far from safe underfoot, even when its thickness is fully a foot of (apparently) solid ice. In general, sea ice does not melt evenly from below, and this uneven melting is undoubtedly due to the fact that the inclusion of the saline constituents on formation of the ice is somewhat sporadic in character, patches of ice poor and rich in salt being formed side by side. The under side of the ice at

this stage is therefore seamed with vertical holes from an inch or two up to 8 inches in diameter and from 1 foot to 2 feet in depth. It seems very likely that the holes correspond in position to those "fibres" which were particularly rich in salt and, from the mode of formation of the ice, it appears probable that the more saline and therefore more easily decomposed "fibres" are those built up of crystals lying horizontal or irregularly oriented.

POND ICE.

The initial stages of the formation of ice on ponds of fresh water, or of salt water, differ little from the modes of formation of sea ice in confined spaces. The growth first proceeds outwards from the shores, by the formation of long needle-shaped crystals which may be straight or only slightly curved. These needles are the visible upper edges of long plate crystals, either lying in vertical planes, or in planes slightly inclined to the vertical (Fig. 28). As in the formation of sea ice in lanes, the plates grow in length, in depth, and also in thickness by the addition of other plates lying parallel to the first. In the spaces left inside the resultant lattice-like formation, other plates form and grow in thickness, with the difference that here the plates generally lie parallel to the surface, and therefore the optic axis is directed vertically upwards. Since, in general, the mechanical movement of the water is less than in the sea, the arrangement and size of the crystals is more regular than in ice forming on the latter. It is, indeed, clear that the relative areas of ice formed from vertical-lying plates and ice formed from horizontal-lying plates must be some complicated function of the temperature and the amount of movement. If the water is undisturbed, the tendency is always towards the formation of vertically-disposed plates in preponderating amount. The structure is also clearly dependent on the area of the pond.

This process is almost exactly the same as that occurring on the surface of freezing sea water, and it seems clear therefore that the actual presence or absence of dissolved salt has little to do with the method of first-growth of ice. It is in the subsequent growth of the pond ice that the greatest differences are observed. Once the first thin sheet of ice completely covers the pond, any further change from water to ice involves an increase of volume, so that the subsequent growth must take place under pressure, directed normally against the bottom, sides, and top of the pond. This pressure can be relieved only by fracture or by bowing of the ice sheet. That pressure actually occurs in such ponds is shown by the miniature fountain of water which rises through any hole made in the ice sheet covering them. Since the growth of the ice is itself the cause of the development of pressure, it is clear that this pressure will increase as the ice thickens, unless the sheet is fractured. As the sheet of pond ice increases in thickness the pressure increases rapidly until it may become very great indeed, while only locally does the pressure at the lower surface of sea ice exceed the weight of the superincumbent ice. Even in land-locked bays and along an irregular coastline where the sea ice is prevented from rising and falling freely with the tides, the pressure will seldom be greater than that of a column of sea water equal in thickness to the ice. Water

may often be observed to overflow through tidecracks in sea ice, but it will always be seen to do so gently.

Actually what is observed in the case of pond ice, whether fresh or salt, is that, after the formation of the first thin ice-covering, growth apparently takes place by the addition of plates with their planes horizontal or inclined at small angles to the horizon—that is with the optic axis vertical, or almost so. It is difficult to explain why this fact should lead to regularity in the cross-section of the prism-like crystals which often result, but this regularity is confirmed by many observations, and is a remarkable feature, particularly in the ice of Antarctic lakes, though it is possible this is brought about by a subsequent change.*

The difference between sea ice and lake ice is therefore one which is only made evident when the ice has reached a thickness of half an inch or more, and the similarity of the structure of ice formed on brine pools to that formed on fresh-water lakes shows that this difference is not due to the dissolved salt in the liquid.

Sea ice we have already described as fibrous, on account of the fact that it fractures easily in directions perpendicular to the plane of flotation. Though, in the case of pond ice, the great majority of the plates making up the individual crystals are oriented so that they lie in a plane perpendicular to that occupied by the similar plates in sea ice, the fracture is also vertical, if the ice contains sufficient salt between the crystal boundaries. Pond ice formed on salt lakes can therefore be truly described as "fibrous." This term, however, cannot be applied to ice sheets formed on fresh-water ponds, since the amount of salt is here, except in rare cases, insufficient to facilitate fracture along the crystal boundaries rather than fracture in any other direction. In the Antarctic, however, really fresh water is not common in ponds, so that the term "fibrous" may be applied to pond ice in the majority of cases.

It is a matter of common knowledge that the fascinating form of ice known to us in our youth as "rubber-ice," owes its properties to the inclusion of small amounts of cryohydrate at the crystal boundaries. This cryohydrate is liquid at high temperatures, and thus allows a certain degree of motion between the individual crystals. The "rubbery" condition of the ice is best developed in warm weather when the ice is in process of melting, and under such conditions it can be broken up into long cylinders of polygonal cross-section which lie perpendicular to the plane of flotation.

The foregoing discussion should make clear the essential difference between sea ice and ice formed from salt water under pond conditions, and between the latter and fresh ice formed under similar conditions. These differences may be summed up in a few words as follows :—

The first layer of ice formed in ponds, whether the water be salt or fresh, differs from the first layer formed on the surface of the open sea, solely in that the growth is, in the former case, predominantly from the sides, which act as points of support for the framework of crystals. Thus, in pond ice, the first formed crystals are more regularly disposed and are larger than those of surface sea ice. All ice formed in ponds

* Pressure changes, for example. (*Vide* Chapter IV.)

after this first coherent sheet is completed grows under increasing pressure, and the crystals ultimately have their optic axes arranged vertically. In sea ice, on the contrary, the majority of crystals, except in the surface layer, which is subject to wave agitation and where therefore the crystals are irregularly disposed, have their optic axes directed horizontally. The essential difference between pond ice formed from brine and that formed from fresh water lies in the amount of salt included between the crystals and between the individual elementary plates which go to make up a single crystal. The outward and visible sign of salt ice is a readiness to fracture along these boundaries of weakness.

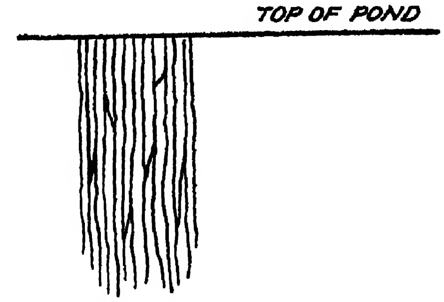


Fig. 34.—Structure in pond ice.

It is in clear pond ice that one sees best another indication of structure in ice crystals formed from water. In a vertical section of clear pond ice an inch thick, it is often possible to recognise a number of very fine lines, usually not absolutely straight, running in a direction perpendicular to the plane of flotation. The significance of these lines does not appear quite clear, but obviously it is in some way connected with the formation of the ice from horizontally-lying plates. (See Fig. 34.)

An example has already been cited to show how the ice formed on almost fresh-water ponds may occasionally break up into individual prisms. Much more striking, however, are certain analogous forms associated with the formation of ponds and lakes on snow-covered glacier surfaces. These snow-filled depressions are frequently filled with water; later the water is allowed to drain away, sometimes by the breaking down of an ice dam, more frequently by the formation of a crevasse. If the temperature is sufficiently low when the depression is first flooded, a sheet of ice forms on the surface, consisting of clear vertically-directed prisms separated from one another by boundaries containing a very large amount of air. As the water surface slowly subsides, the clear prisms grow downwards and the air entangled with the snow is still segregated in the boundaries between them. Quite commonly, prisms formed in this manner may have a diameter of 2 or 3 inches and a length up to 2 feet. The prisms, however, are never of constant cross-section. At times, this structure of ice possesses quite a level upper surface and forms a good surface underfoot.* On the other hand, a great deal of this type of ice consists of irregular sharp ice columns separated from one another by spaces of 3 or 4 inches which originally contained the segregated air. This form of surface received the name of "bottle-glass" ice, chiefly because the columns are sufficiently sharp to cut.

Ice Formed on Streams.

The method of formation of ice-coverings on streams is almost exactly analogous to that on ponds or lakes. The first thin covering is by long fan-shaped plates lying perpendicular to the surface, the interspaces between these being afterwards filled

* They have actually been used as camping spots, owing to the evenness of the surface in comparison with the general roughness of the glacier surface where covered with ablation pits.

in by horizontal-lying plates. Owing, however, to the movement of the running water, the vertical plates are unable to grow undisturbed, and do not reach the size they attain on the surface of ponds. The same movement of the stream is also responsible for retarding the growth outwards from the banks, since the newly-forming plates are liable to be swept away by the stream. As in the case of pond ice, subsequent growth proceeds largely by the addition of horizontal-lying plates to the lower surface of the sheet, but the growth is never so regular and the " fibrous " quality of the ice is much less pronounced.

In the ordinary brook, in which the stream velocity varies from place to place, the rate of freezing also varies in such manner that the brook remains open longest where the stream velocity is highest. This is due largely to the mechanical action of the current which has been mentioned. The small plates forming in swift water are carried down with the current to positions of lesser stream-velocity, and are there deposited to add to the ice-covering. Though, no doubt, a certain fraction of the ice deposited in quiet portions of the stream is due to the addition of plates torn off in this way higher up, and yet more to those formed *in situ*, still, when falls and rapids exist, the major part of the ice must be formed as frazil crystals caused by the quick cooling of the water by mixture with cold air. At times, the amount of this frazil-ice is so great that the stream may become completely blocked at certain points, with the result that the upper surface of the ice becomes flooded by the downflowing water. The ice sheet then increases both from above and below. In all such cases, the structure of the ice is obviously very complicated.

Mention has already been made of the form assumed by the surface ice of such streams when the water drains away and leaves the ice sheet attached to the banks and sagging under its own weight. Another interesting formation which is probably best treated in this section is quite commonly found on the underside of such curved sheets. As the water drains slowly away from underneath the ice covering, it may remain in contact with certain portions of the latter after an air gap has been formed everywhere else. If the process of draining is afterwards sufficiently slow, the ice may continue to grow at this point, though once an air-gap between the ice sheet and the water has developed, the small thermal conductivity of air puts a stop to the formation of a second complete ice sheet on the water surface. Meanwhile, conduction through the ice near the line of contact between ice and water permits further ice growth at this line, so long as the rate at which the water sinks from the ice sheet does not exceed the speed at which the ice grows downwards. If the sinking of the stream level is stayed altogether for a period—for instance, by a spell of comparatively warm weather—the local growth will continue, not only downwards, but also in a lateral direction. In the course of time, an ice pillar of greater or less thickness may be formed with local annular projections corresponding to the pauses in the general sinking of the water level. Finally, when all the water has drained away, the ice sheet remains supported, partly by the banks and partly by these ice columns which occur at irregular intervals throughout the course of the stream (Plate LXXVIII).

Icicles.

The formation of icicles in the Antarctic is similar to their formation in temperate regions. Two conditions are therefore necessary before icicles can appear: First, water must be present; and second, at the point where icicles form, the temperature must be low enough to cause a portion of this water to assume the solid phase. Since the formation of water argues a high local temperature, it follows that the source from which the water is derived cannot become the *point d'appui* of the icicle, though alternations of direct sunlight and shade may produce icicles from water which has not travelled very far.

Three essentially different methods of formation may be clearly distinguished :—

(1) From fresh water (Plates LXXIX and LXXX)—
   (*a*) From water formed by the sun's action on clear ice.
   (*b*) From water formed by the heating effect of rock or silt on fresh ice.

(2) From sea water.

(3) By the addition of drift snow to brine-tipped icicles of Type (2).

1. *Icicles formed from Fresh Water.*

This method may be called the normal one. As the water trickles slowly down to fall on the ground below, a certain proportion is solidified, and the projection increases in thickness, and grows downwards in the shape of an inverted cone.

Once the icicles are formed, they grow in thickness and in length whenever the meteorological conditions are favourable, until finally the weight of the mass overcomes its cohesion, or (more commonly) the cohesion of the ice or snow projection from which it depends. In the first case, the icicle itself will break somewhere near its top; and, in the second case, as more usually happens, it will break off a portion of its foundation. A transverse force is always a more effective agent of destruction than a longitudinal force, and, after a strong gusty wind, any exposed and yet shady portion of the Antarctic coast may be seen in summer to be strewn with the remains of icicles which have given way under the impact of the gusts. Very commonly, the base of the icicle is supported by a projection which is close to the ground. The icicle then advances until it meets the stalagmitic growth which is rising from beneath to meet it. In this way, a pillar is formed which may grow until it is more than a foot in diameter. A good example of such a pillar is seen in Plate LXXXI, which shows an icicle which has grown down into the snow-drift resting on the sea ice at the foot of the glacier cliff from which the icicle is depending. A few days before the photograph was taken, horizontal movements of the sea ice to which the lower portion of the icicle was cemented had caused the latter to break in the middle, and the lower portion had been carried slightly away from the upper.

The best case of such a series of icicle pillars is recorded from Butter Point, in 1908. Here the snow cornice had sagged along the face of a low ice cliff, and the icicles which depended from it had been driven into the snow-drifts at the base of the cliff. Movement of the cornice was then suspended for some time, and the icicles increased

in thickness and became firmly cemented to the drift. A few days elapsed and then the snow cornice once more began to sag, quickly in some places, more slowly in others. The quick movement naturally resulted in the wholesale destruction of the icicles along considerable stretches of the ice face. Where movement was slow, on the other hand, the icicles adapted themselves most wonderfully to the new conditions, bending freely under the slow steady strain, until some of them had assumed the shape of a roughly-made letter S and others had been bowed into an excellent V (Plate LXXXII, Fig. 35). The result at the bend was commonly to flatten the section, as in a badly-bent piece of glass-tubing.

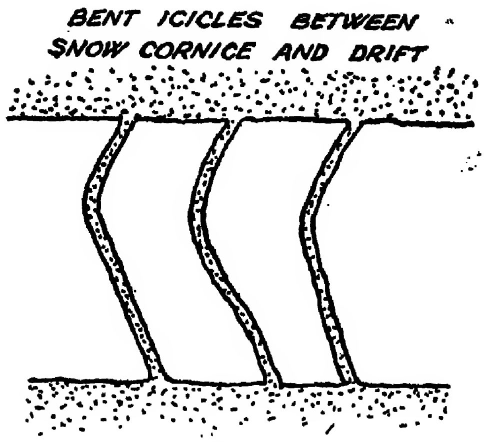


Fig. 35.

The most favourable conditions for the formation of fresh-water icicles occur when the upper portion of an ice face is exposed to the direct rays of the sun, while the underside of the projections from which the water drips is in shade. This is a conjunction of circumstances which occurs very commonly along the sides and ends of all glaciers, and on snow cornices in sheltered positions, so that in summer icicles of this type are very common. The effect of the presence of rock, silt or dark objects of any description is still more marked, and, wherever such objects occur in, on, or around glaciers and snow-drifts, icicles may be expected at one time or another. Often those found on the rocks themselves will be very evanescent, as, when the rock is directly exposed to the sun, the heat will be too great to permit their survival.

The chief difference between icicles formed by methods 1 (*a*) and 1 (*b*) is that the latter type may occur, in the vicinity of rocks and other objects of dark colour, even in shade and at temperatures far below freezing-point, the place of direct sunlight being taken by radiant heat emitted from the dark objects.

2. *Icicles formed from Salt Water.*

The above method of growth may also occur if the water, or the ice from which the water is formed, contains a greater or less proportion of salt. In this case, the process consists chiefly in the abstraction of fresh water from the brine and its change into ice. A little of the salt, therefore, may be included in the upper portion of the icicle, but by far the greater amount will collect near to and at the tip. If the air temperature is only slightly below freezing-point and the growth of the icicle is thus fairly slow, the ice remains almost fresh and the tip may be almost as sharp as that of the typical fresh-water icicle (Plate LXXXIII). The concentrated brine at the tip of the icicle will remain unfrozen at any but very low temperatures, when it will solidify in the form of an opaque white patch which is found on examination to be a mixture of cryohydrates. The low freezing-point of this brine causes the icicle tip to remain moist for a considerable portion even of the Antarctic autumn and winter; and this has a distinct significance when considered in relation to the formation of icicles of the third type.

Before going on to a description and explanation of this third type, there are one or two processes causing modification of icicle form which need to be mentioned.

These modifications are introduced when the icicles form on surfaces which are either in reach of the direct laving of the sea, or within the reach of sea spray during gales. They have, therefore, especial reference to icicles formed along the Antarctic icefoot. Here we have to consider the effect of large quantities of salt water on icicle formation, and also of another factor of still greater importance, namely, the lowness of the air temperature at which such icicles are able to form. It will be seen from a mental review of the conditions, that these temperatures are only limited downwards by the temperature range along the Antarctic coast in the presence of open water.

Icicles formed under these conditions of low temperature and containing excessive amounts of salt water, will naturally be among the most common of Antarctic types, since they are not affected by any nice adjustment between air temperature and ice temperature, but may grow whenever the air temperature is low, that is for some eight

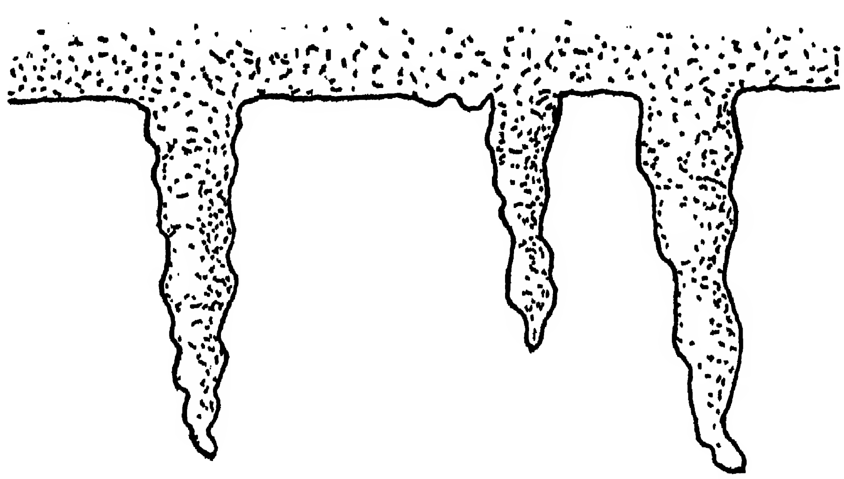


Fig. 36.—Bulbous and rounded icicles formed from salt water.

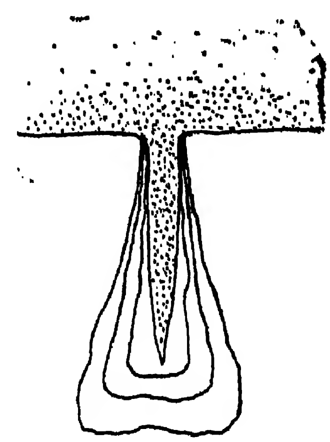


Fig. 37A.—Bulbous icicle formed from blown spray.

months of the year. They are, as already hinted, less widely distributed than the other types, since they can only occur in immediate proximity to the sea.

The most noticeable characteristic of such icicles, as opposed to the types already considered, is the fact that they do not end in a fine point, but more commonly have a rounded or even bulbous extremity, as in Fig. 36 (Plates LXXXIV and LXXXV). This is due partly to the low temperature at which they are formed and partly to the large quantity of salt which enters into their composition. Two distinct modes of formation may also be recognised in this type of icicle :—

(*a*) From sea spray which has been hurled far above the sea, and has then trickled down the rock or ice of the cliffs or icefoot lining the shore (Fig. 37A; Plates LXXXVI and LXXXVII), and

(*b*) By additions to icicles formed in either of the preceding ways, additions made either through the laving action of the waves, or by the rise and fall of the tide (Fig. 37B).

The chief differences between the two sub-types will be considered in the section on the structure of icicles. They do not differ much in appearance to the naked eye, except in isolated cases. Two cases, however, do occur when icicles formed in the latter way are very easily recognisable.

The first is seen when the icicle is formed either by the laving of an original icicle by tides, or by waves during the final phase of a blizzard, when the sea is subsiding. The shape of icicle formed in the first case can be gathered from Plate LXXXVIII.

The second case occurs when a number of icicles depending from the undercut edge of an ice-foot form very close together, and are laved only by the highest spring tides. Here the whole series may be joined up, as often occurred at Cape Adare, by a miniature tidal platform a few inches thick, presenting an appearance which is shown diagrammatically in Fig. 38.

The particular case where a composite icicle is formed was well seen at Cape Adare, and one result, where the icicles have grown significantly by the deposition of hoarfrost, is figured in Plate LXXXIX. There were numerous icicles along the Ridley

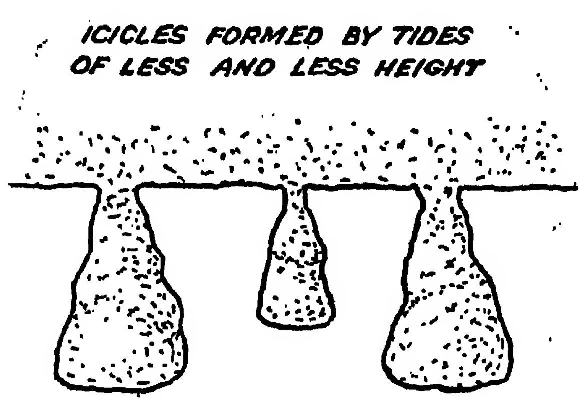


Fig. 37B.

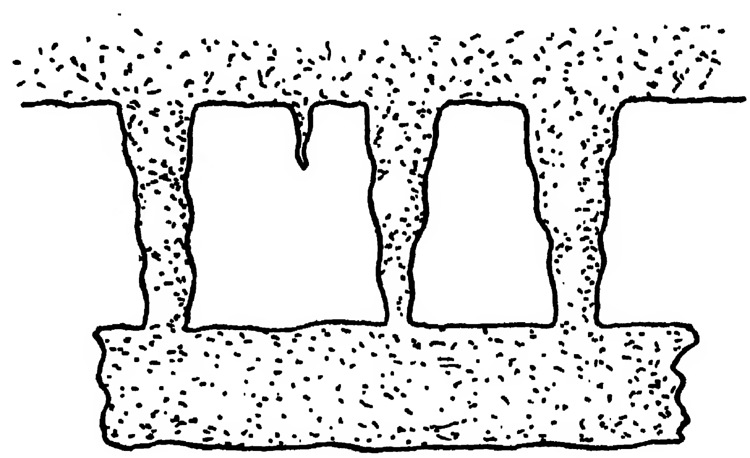


Fig. 38.—Icicles joined by a miniature tidal platform.

Beach ice foot which had been formed after methods 1*a*, 1*b*, or 2*a*, by the slow freezing of water dripping either from fresh or salt ice blocks. In either case, the result had been to form sharp-pointed icicles of black clear ice. Either through the agency of the spring tides, or through accretion of spray during the March blizzards, these icicles next became coated with a uniform layer of white, greasy-looking salt ice (formed under conditions of deposition such as occur along the icefoot under storm or tidal conditions). After the end of the storm, or at times of low tide, the normal fresh-water ice was again formed, and thus an icicle was built up which showed in section a number of concentric rings (Plate XC).

Whatever the shape of icicles formed under either of these two conditions may be, the low temperature present at the time of formation of at least some layers will cause the inclusion in the ice of a large quantity of brine. Whenever, therefore, the temperature rises above the cryohydric temperature of any of the salts in this brine, that salt goes into solution in water obtained by the melting of a little of the ice in contact with it. Under the influence of gravity, the solution then slowly drains downwards through

the ice, until the brine is all collected at the lower end of the icicle. The tip will thus be kept moist, except when the temperature is low enough to form cryohydrates of *all* the salts concerned. This form of icicle, therefore, as will be seen later, is eminently suited to form a basis for the inception of the third type.

3. *Icicles formed by the addition of Drift Snow to brine-tipped Icicles of Type* 2.

Prominence has been given in the earlier pages of this memoir to the fact that the strong, drift-bearing winds of the Antarctic are very usually accompanied by a relatively high temperature.

In consequence of this high temperature, and of the processes described earlier in the chapter, it follows that in most blizzards all icicles formed from salt water will have moistened tips. The effect of the impact of the drift against the moistened surfaces of such icicles will be self-evident. During each blizzard, the amount of snow added to the icicle by adhesion to the moistened tip will be regulated by the amount of brine available to soak through the new ice, and thus the growth of this form of icicle will be slow. After such succeeding blizzard in the autumn, winter and spring, low temperatures once more resume their sway, and so the seepage of the salt through the ice formed by addition of drift snow will be still more delayed. The action proceeds with every rise of temperature, however, and before a new wind springs up the chances are that the icicle will again have a moistened tip. Each blizzard usually adds its quota of snow to the icicle, until the salt solution is so diluted that draining is almost imperceptible.

The form of these drift icicles depends on the amount of shelter afforded by the position in which they have been formed, for this factor decides whether the wind will be constant in one direction, alternately from opposed directions, or from no particular direction. Three main types of shape may be distinguished accordingly.

The first type (Plate XCI) is the most characteristic of all the Antarctic forms of icicle, and has been extensively figured in the records of previous expeditions as the "foot stalactite." Such icicles are to be found along those portions of the icefoot which are only slightly sheltered from the wind, and where, therefore, the drift-bearing gales still keep their main direction, whether south-easterly, as is usually the case, or westerly, as occurs opposite the main outlet glaciers on the north coast. In such a position, the gale is extraordinarily steady in direction, and, the drift always striking the icicle from the same direction, the projection is built out in the form of a foot-like extension. The foot-form is naturally assumed, because the lowest portion of the icicle is the most moist and, on this level, the drift ice becomes soaked more quickly and more thoroughly. It is thus in each wind the last portion of the icicle to take up fresh additions. Good examples of these foot stalactites are to be seen on the right of Plate XCI. On the left, on the same plate, are seen examples of the stalactites we compared with ponies' legs on account of the striking resemblance. They are caused in icicles which for any reason are excessively salt, by the drooping under its own weight of the toe of the foot as it gets soaked with brine. Unusually warm spells, when the

brine is able to take up a considerable quantity of water, as in direct sunlight in the early spring, may cause the formation of icicles of Type 2, dependent from foot stalactites of Type 3 (*a*) (Plate XCI).

The second case of drift-icicle formation (Type 3 (*b*)) is to be seen wherever, as under a steep cliff like the end of Cape Adare, the lee is more perfect, so that the wind, which is here normally E.S.E., blows now from this direction and then from the opposite direction. On several of our sledging journeys, we had undoubted proof of a dual direction of the wind which gave us much trouble in our camping arrangements. It was this which caused us first to pay attention to the other phenomenon undoubtedly due to the same cause. At two or three places where we camped, drift-bearing southerly gusts alternated with drift-bearing northerly gusts, and here it was that the curiously shaped icicles which are figured in Plate XCII were formed.

The third and last type of drift-icicle we observed (Type 3 (*c*)) is figured in Plates LXXXIV and XCIII. In these cases, the lee was so perfect that the snow came from no particular direction but fell in an eddying swirl, and the icicles formed were, in consequence, often club-shaped, with a bulbous protuberance at their tips. Plate XCIII shows the type of bulb formed when the drift has free access to sharp icicles formed from spray at a fairly high temperature, and which had, therefore, only a slight amount of salt in their composition. Plate XCIV, on the other hand, shows the rougher, coarser type of bulb formed on spray icicles which were themselves deposited quickly at low temperatures and so had a greater saline content. The flattish, forward-springing nature of the drifted portion of the icicles in the latter plate is due to the fact that the drift snow was deposited more at the front than at the back of the icicle.

Structure of Icicles.

If horizontal sections of icicles of Type 1 or 2*a* be examined in the polariscope, they occasionally show a very instructive arrangement of the individual crystals, as may be seen in Figs. 39A and 39B. The core near the base of the icicle is formed of a great number of very small and approximately circular grains, and this is surrounded by an outer layer of larger crystals whose average length is three times their width.

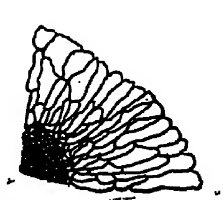


Fig. 39A.—Ice grains in icicles (vertical section). Natural size.

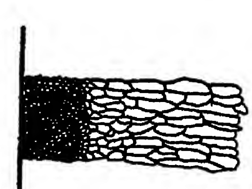


Fig. 39B.—Ice grains in icicles (horizontal section). Natural Size.

These outer crystals are so oriented that the major axes of the grains are arranged in a radial direction.

A horizontal section near the tip of the icicle differs by the absence of any definite core, so that the radial arrangement of the crystals appears much more pronounced (Fig. 40).

The crystalline structure of fresh-water icicles seems to vary considerably, as an examination of similar sections of other icicles frequently showed no signs of such a radial arrangement of the crystals. From evidence based on the manner of deposition of hoar-frost crystals on icicles, we have been led to the conclusion that the optic axis of such crystals usually points outwards from the centre in a radial direction, and is, therefore, approximately, perpendicular to the freezing surface at every point.

Perhaps the period when icicles formed of pure clear ice are best examined with a view to the elucidation of their crystal structure, is when they are being gradually melted under the influence of direct sunlight. As is the case with glacier ice, the melting proceeds fastest in the boundaries between the individual crystals. The

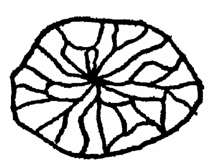


Fig. 40.—Grains at tip of icicle (horizontal section). Natural size.

Fig. 41.—Grains at tip of icicle (vertical section). Natural size.

structure is, therefore, emphasized by the film of water which separates them, and the radial structure of the icicle can then be seen very well. The best example of this was seen one summer at Butter Point. Here the icicles, in which the only sign of melting was the inception of a network of fine lines upon the surface, were so rotten that they could be crushed in the hand and the water literally wrung out of them. When such icicles were snapped across, the radial arrangement of the crystals was seen to be most pronounced. In this case, certainly, the radial habit continued right to the centre of the icicle, though it is of course possible that it might be a secondary structure due to molecular re-arrangement.

Icefoot and Tidal Platform.

Another important mode of formation of ice from water is exemplified by the growth of the icefoot during the autumn and winter. The formation of an icefoot by the freezing of sea water is somewhat analogous to the formation of sea ice, but it differs from the latter by virtue of the fact that the main growth of the icefoot usually takes place at the surface, or above the surface, of the sea, and chiefly as the result of the laving action of tide or waves, or of spray carried by the wind. The structure of the icefoot therefore differs from that of sea ice, firstly through the inclusion of a greater amount of air, and secondly in the occurrence of much smaller and less regularly arranged crystals. It is not at all "fibrous." In fact, the structure of the ice in an icefoot approximates to that of glacier ice, from which it is readily distinguished, however, by the larger and more irregular inclusions of air, by its salinity, and often by a regular layered structure due to alternate immersion in and emersion from the waters of the sea.

This resemblance to glacier ice is often increased during the course of the winter by a molecular change which takes places within the ice, which results in the inception of a granular structure much the same in size as that in the ice of the clear bands of an Antarctic glacier. This change has, unfortunately, not been studied in detail, but, at Cape Adare, a boulder which was known to consist of glacier ice covered with a foot or so of spray ice, in time developed in its outer layers curiously-shaped patches of clear bubble-free ice which, when subjected to the etching action of a gentle heat, proved to consist of grains of appearance identical with the glacier grains of the boulder beneath, though they far surpassed them in size. The formation of these clear patches was accompanied by the appearance of large druses several cubic inches in capacity containing a mixture of air and fine powdery ice.

The method of formation and growth of the Antarctic icefoot will be treated more fully in Chapter IX.

Glacier Ice.

The distinguishing characteristic of ice crystals formed directly from water (with the possible exception of this last type) is best described as a tendency to angularity combined with regularity in shape. This results simply and logically from the tendency of ice to assume a plate form on separating out from freezing water. We may, in fact, look on ice formed in such a manner as simply built up of elementary plates oriented in appropriate directions.

Quite different is the manner of formation of glacier ice which, in the Antarctic, takes place almost entirely by the growth and modification of fallen snow, which is nearly always formed in the absence of water. As a result of this we have found in typical Antarctic glacier ice no visible *forelsche streifen* or other evidence of "elementary plates" within the glacier crystal, though it is clear that in more genial climates, where water occurs abundantly, the *streifen* are likely to be quite well marked. The framework of an Antarctic glacier crystal is not formed from individual plates, as in the case with crystals separating out from water, and it is not surprising that the angular character of the water-formed crystal is not duplicated in the completed glacier grain. The original deposit of snow may be either in the form of stars, plates, prisms, or irregular grains, though as a rule wind action or thaw may cause the majority of them to become fragmentary or shapeless before the gradual change to ice sets in. After precipitation, certain more favoured crystals (perhaps by accident of size, perhaps by accident of orientation) will grow at the expense of others. The form assumed by the completed crystal is roughly polygonal in section.

The rate of change to ice is dependent on temperature, and thus the change may be completed in a few days in temperate climates, though requiring weeks for its completion on such glaciers as the Ferrar in high southern latitudes. The extreme case that has come within our experience is that of the Ross Barrier, where the mean yearly temperature is about 15° below zero Fahrenheit.* The snow here has still a definitely

* *See* Amundsen, 'The South Pole.'

angular form some years after its deposition. Even more extreme temperatures are found on the plateau, the mean temperature in January, 1912, being not far from −20° F.

In temperate climates, therefore, the result after quite a short time is the formation of a subangular polygonal grain such as is shown in section in Fig. 43, while in the Antarctic a short time has little or no effect and, even after a considerable lapse of time, the ice still exists in an incompletely crystalline form as shown in Plate LII. Quite commonly, the original crystals are segments of coarse hexagonal plates, but incomplete hollow pyramid forms are also common.

After two years—that is, at a depth of about 2 feet on the Ross Barrier—the individuals still preserve this form, and almost one-half of the total bulk of the Barrier at this depth consists of air included between the individual crystals. These grains are of very irregular shape, but most surprising is the fact that, with all this air between the grains, the surface is often quite hard, so that it is very difficult to make any impression with the shovel. In a still more frigid climate, as on the King Edward VII plateau at an elevation of 9000 feet, the change from snow to *névé* takes place even more slowly, and a note by Lieut. Bowers at the South Pole states that, "For walking on foot, the ground is all pretty soft and, on digging down, the crystalline structure of the snow is found to alter very little and there are no layers of crust such as are found on the Barrier. The snow seems so lightly put together as not to cohere, and makes very little water for its bulk when melted."* Hard *névé* did indeed occur on the crests of the greater undulations on the plateau, but these are the positions where the wind is able to exert its maximum force, and so to sweep away all the overlying snow and keep the same surface always exposed to the rays of the sun.

Size of Glacier Grains.

Mention has been made that the rate of growth of certain crystals at the expense of others is dependent on the temperature, and that growth of the larger crystals takes place at the expense of the smaller ones. If this held good, whatever the size of the crystal, there would be no limit to the size these might attain. Observation makes it quite clear, however, that whatever the reason may be, there is a limit to the size attainable by the glacier grain, and that this limit varies for different situations. Examination in the polariscope of a number of sections cut from glacier ice is sufficient to show that there is a mean size of grain at any particular portion of the glacier, and that the grains in any one place are fairly constant in size. Very large and very small grains occur only rarely (Figs. 43–46).

A certain amount of data has been gathered on the subject of the mean size of the glacier grain, but the observations are more qualitative than quantitative. J. Y. Buchanan has, for instance, made a number of observations on the size of the glacier grains in the Great Aletsch Glacier. The method he used was that of taking a block of glacier ice and exposing it to the action of the sun's rays so that it became disarticulated

* Another note states that a stick could be easily pushed 6 feet into the snow.

into its constituent grains. The weight corresponding to a counted number of grains then gave the data for the determination of the mean weight of the grain. An analysis of his results is given in Table IV and shows, for this portion of the glacier, a mean weight

TABLE IV.—Buchanan's Results.

Average weight of grain.	Calculated diameter of average grain.
Grms.	Cm. = In.
30·1	4·0 = 1·6
28·5	3·9 = 1·76
48·0	4·6 = 1·84
102·0	5·9 = 2·36
25·3	3·7 = 1·48
16·8	3·2 = 1·28
58·3	4·9 = 1·96
Mean 44·1	4·5 = 1·8

of 44·1 grams, corresponding to a mean diameter of 4·5 centimetres. These results must be only approximate, since two important sources of error enter into the calculation. These errors are :—

(1) The loss from each grain by melting and evaporation during the disarticulation of the grains, and

(2) The reduction in the number of grains through the melting and overlooking of the smallest individuals. At first sight, it would appear that these two errors might neutralise one another, but it is probable that the second is much more important in its effects than the first.

Other estimates of the mean size of the grain may be made from the figures and diagrams given in the various papers by R. M. Deeley, and in the publications of the Greenland Expedition under the leadership of E. von Drygalski. These results are best expressed in mean diameter of grain obtained by calculation from the total number of grains contained in a given area of the section.* They are set down in Tables V and VI. Finally, we have the estimates of the mean diameter of the glacier grains in sections taken from the Ferrar, Taylor, and Suess glaciers in the Antarctic. For the last measurements, the mean size of the grain is obtained, sometimes by simple estimation in the polariscope, but more commonly from actual diagrams made on the spot. In neither case can the results lay claim to any great degree of accuracy, but they cannot be far from the truth. The mean of all observations gives a diameter of $\frac{3}{16}$ inch, which is only half that recorded by Deeley and Fletcher.

During the first western geological journey to the Ferrar Glacier region, a very great number of sections were made from glacier ice, with the object of determining

* The area of the section was measured directly by planimeter.

not only the mean size of the grain and its shape, but also the variations in size and shape of grains from different portions of the glacier.

TABLE V.—Drygalski's Results.

—	Area.	Number of grains.	Mean size of grain.
	Sq. cm.		Cm. In.
Abbildung 42...	59·3	11	2·3 = 1·0
43...	7·6	3	1·6 = 0·6
44...	12·9	6	1·5 = 0·6
45...	9·2	16	0·75 = 0·30
46...	21·0	10	1·4 = 0·56
47...	6·4	8	0·9 = 0·36
48...	5·8	8	0·85 = 0·34
49...	8·1	7	1·1 = 0·44
50...	16·9	8	1·5 = 0·6
			Mean 1·32 = 0·53

TABLE VI.—Fletcher and Deeley's Results.

—	Area.	Number of grains.	Calculated mean size.
	Sq. cm.		Cm. In.
Fig. 1	58·6	19	1·9 = 0·76
2	39·8	63	0·8 = 0·32
3	16·8	40	0·65 = 0·26
4	11·4	14	0·9 = 0·36
5	12·8	17	0·87 = 0·35
6	3·0	3	1·0 = 0·40
			Mean 1·02 = 0·40

As an illustration to show the order of differences found, an analysis is given of the observations made on the ice of the Suess Glacier, a former tributary of the Taylor Glacier which is shown in Fig. 42. On this figure are marked the positions from which the various sections were taken. All sections, unless otherwise denoted, were taken from a depth in the ice of 8 inches, and, if from a vertical wall, at a height of 2 feet above the silt bottom.

The following descriptions of the sections are taken from the field note book :—

Section E (see Fig. 43). — Very many air bubbles—mostly pear-shaped. Grains all rounded and of irregular shape.

Section G.—Grains $\frac{3}{16}$ inch across on an average and very regular in size. Grains larger than in last section. Bubbles the same as in last section.

Section D (see Fig. 44).—If anything, grains still larger and apparently more rugged or angular. Lines of bubbles here mark the position of a fine crack and also form the boundaries of the adjacent grains. Bubbles elongated with maximum length three times the breadth.

Section S (see Fig. 45).—Grains much smaller. Cracks, marked by lines of bubbles, sometimes cut across grains and sometimes not. Average diameter of grains $\frac{1}{16}$ inch. They are very regular in size and less angular than in the last section.

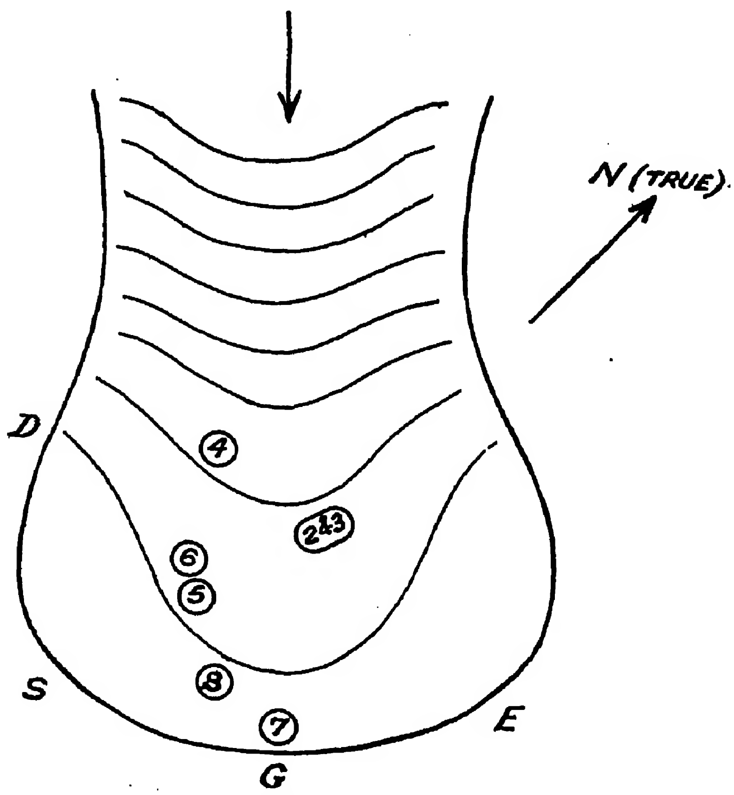


Fig. 42.—Diagram of Suess Glacier (Taylor Dry Valley), showing positions from which samples were taken.

Section 1.—Clearish ice. Grains are large ($\frac{3}{8}$ inch), one reaching $\frac{5}{8}$ inch in diameter. No discontinuity of the crystal boundaries at the line of bubbles representing old cracks. Most bubbles are circular. Sections from the white bubbly ice near by show grains of much smaller size.

Section 2.—Névé. Small and quite angular grains, the greatest being $\frac{3}{16}$ inch across. Bubbles never vary greatly from spherical shape.

Section 3.—Dark glacier ice. Bubbles evenly spaced, nearly spherical and larger ($\frac{1}{32}$ inch). Grains on average $\frac{1}{4}$ inch across and quite irregular in size and shape.

Section 4.—Most grains $\frac{1}{2}$ inch in diameter, average $\frac{3}{8}$ inch. Bubbles large and round. Boundaries of grains sub-angular, mostly rounded at the corners.

Section 5.—Small $\frac{1}{8}$-inch grains, except those touching a few grains of sand. Here grains increased in size up to $\frac{3}{4}$ inch. (Only the larger abutted on the silt.)

Section 6.—Grains sub-angular, average diameter $\frac{3}{16}$ inch. Bubbles almost all circular.

Section 7.—Angles more rounded; otherwise same as last section.

Section 8.—Same as 7, but bubbles bigger and more irregular in shape and size. Section from surface of the ice.

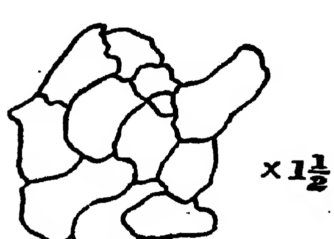


Fig. 43.

Fig. 44.

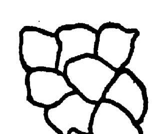


Fig. 45.

Figures showing glacier grains.

Analysis of the above observations is not without interest. The mean size of the grain seems to be about $\frac{3}{16}$ to $\frac{1}{4}$ inch, but the variations in the size of the grain

can seldom be referred to a definite cause. This, however, is not the case in Sections 1 to 3. These sections were taken from a portion of the glacier where the ice was a breccia of blue ice, grey bubbly ice, and névé, and had been formed, at least on the surface from which the sections were derived, by avalanche and drift snow further up the glacier. In this series of sections, the névé was evidently of more recent formation than the greyish bubbly ice and still more recent than the clear blue ice. A comparison of these three sections thus affords clear evidence that the glacier grain becomes larger as the air is expelled from the mass. There seems also to be a tendency towards greater angularity in the névé form. Section 5 is also of great interest, in that it shows how the size of the grain increases out of all proportion in the near presence of a few grains of sand. Whether this is due to the bathing of the crystal in water, as Drygalski maintains, or is due simply to the higher temperature brought about by radiation, must remain an open question. Finally, in Section D, we see that former cracks in the ice are shown up as lines of small bubbles, and that these same cracks here form the boundaries of the crystals. From Section S, on the other hand, we learn that some of the fossil cracks form the boundaries of the crystals, while others do not. This observation (noted also on other occasions) is of importance, in that it shows how the modification and growth of the grains continues at all times, so that a small fault may soon become cemented again, remaining visible in the section only as a plane of bubbly ice. (Fig. 46.)

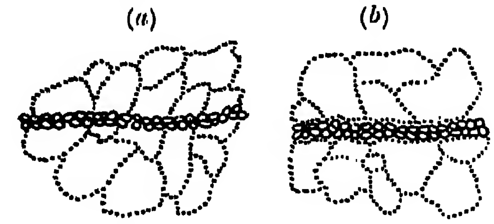


Fig. 46.—Glacier grains (a) traversed by a line of bubbles; in (b) the bubbles lie in the boundaries of grains.

It has been clearly stated by Drygalski, though he has not given quantitative data, that in Greenland the size of the glacier grain is dependent on the altitude at which it is formed. Our observations encourage us to put this statement in a more concise form. The mean glacier grain will be smaller the lower the mean annual temperature.

In the particular case where the temperature rises to freezing-point and the mass is bathed in water, the growth is exceptionally quick, and the mean size of the glacier grain significantly greater than that we have observed generally in the Antarctic. In fact, the largest glacier grain we have observed was hardly equal to a small walnut in size, while Drygalski reports that single grains in the warm summers of Greenland may reach double the size of a closed fist. The observations in the Ferrar Glacier region show a remarkable uniformity in size of the glacier grain in the grey bubbly ice and, quite frequently, a mean size twice as great in the bands and strata of clear ice which occur within the body of the glacier. The one merges gradually into the other, however, without the slightest discontinuity. This difference in size of the grains is very strong evidence in favour of the view that the clear ice is in many cases only normal glacier ice, which has been bathed in water and has in this way become freed from included air bubbles. It is certain, at least, that the ice under the lateral moraine of the Koettlitz Glacier is very frequently bathed in water, and here we find that the average diameter of the grains is no less than $\frac{3}{4}$ inch. Glacier ice further north, in the Cape Adare region, is composed of grains of larger size than are found further south.

A favourable opportunity for studying the effect of water on the glacier grain is seen in the walls of crevasses which at one time or another have been water carriers. These are very numerous in the cliff face of some glaciers, and in all cases the ice which bounds them is of larger grain than elsewhere.

Though, in general, we find that the size of the normal glacier grain varies only within narrow limits about a mean value, still there is one very striking case of abnormal variation. This takes the form of planes or inclusions containing swarms of grains in size very much smaller than their neighbours. These small grains are further distinguished by considerably sharper angles, and approach quite closely to a polygonal section. From the position in which these aggregations are found, it is probable that they are to be referred to cracks and holes which have lately been filled with snow, so that the granular structure is only incompletely developed. They are usually characterised by a very high air content.

Inclusions of Air in Ice.

The occurrence of air included in ice is of considerable importance as an aid in deducing, not only the method of formation of that ice, but also its subsequent history. The reason for this latter statement is clear, when we consider that the air present in snow-drifts before their change into ice is included, not within the crystals, but between them, and that by subsequent modifications the crystals grow in course of time so as to include the air cavities which once marked the boundaries between them.

The best example known to us of the value of this included air as an indicator of past history, is provided by the filled-up crevasses which are elsewhere referred to. The vertical "dykes" of clear ice in Warning Glacier cutting through the ordinary laminated ice of the glacier, could have been formed in no other way than by the filling up of crevasses. Such a dyke is well figured in Plate XCV, while a sample of ice from a similar one is seen in Plate XCVI.

It will be observed that the ice is quite clear, but for an opaque whitish line down the centre, and for long drawn-out air-tubes which run perpendicular to the sides of the "dyke." The conclusion forced upon the observer is that these dykes were originally formed by the growth of long prisms of ice from the sides of the crevasse, a method of growth which is only what one would expect. Corroboratory evidence of this method of formation of the clear ice comes from the glaciers of the Canadian Rockies, where Scherzer* describes these structures in process of formation and before the prisms from either side have joined in the centre. In order to make certain that the air-tubes did actually lie along such natural boundaries, a large piece of this ice was taken back to Cape Adare, and was there exposed to the gentle etching effect of the summer shade temperature, being placed in the loft of Borchgrevink's deserted hut and left there for several days. At the close of this period the ice was examined, and the structure of the ice was found to be etched out on the surface of the block. The interesting feature of the experiment, however, lay in the fact that the structure bore

* Scherzer, 'The Glaciers of the Canadian Rockies.'

no definite relation to the air-tubes but was granular in character. It was, in fact, similar to glacier ice that has been bathed in water. Two things struck the eye at once—first, the large size of the grain compared with the normal Antarctic glacier grain and, second, the long-drawn-out appearance of some of the grains. Clearly the structure was a secondary one which had gradually encroached from the glacier walls on either side of the dyke, but which had not entirely obliterated the original structure on which it was now superimposed. The mode of change is especially well seen at the dyke wall, where those grains of the glacier ice which were fractured when the crevasse formed have grown outwards so that the wall is no longer sharply marked by discontinuity of structure.

Similar cases, where the presence of included air leads naturally to deductions as to the former history of the ice, are to be found in the ice which makes up the main body of a glacier. Let us cite, for example, a typical observation made on February 5, 1911. Samples were taken on this day from different parts of the terminal face of the Suess Glacier, which is seamed with small cracks. Some of these cracks had again become closed, and were then visible as planes of bubbly ice contrasting sharply with more air-free ice on either side. When samples from certain of these fossil cracks were examined in the polariscope, it was found that, in some cases, the planes of bubbly ice were also planes of discontinuity of the crystals, as if an actual slip had taken place, while, in other cases, no such discontinuity of structure was to be seen. In these latter cases, the slip had evidently occurred so long ago that the glacier grains had become rearranged, so that the former plane of discontinuity would have been completely obliterated but for the presence of the bubbly ice (Fig. 46).*

The amount of air included in the whole mass is also of considerable importance from the point of view of the origin of the ice, though the proportion of air to ice does not always vary in the direction one would expect at first sight. Thus, for instance, we might expect that ice formed directly from the snow of a drift lying on a glacier surface would contain a much higher percentage of air than that formed by the freezing of water. This is not necessarily true, however, as will be seen later, since the methods of change from snow to ice and water to ice vary so much with variations in the meteorological conditions. Thus, in the change of such a snow-drift into ice, the usual predominant direction of growth is upwards from the ice upon which the drift rests, so that the greater part of the air between the crystals is able to escape.

This upward growth was well seen in the snow-drift into which the Northern Party dug the snow cave in which they spent the months from March to September, 1912. This drift, as is usual in the Antarctic under similar conditions, had been converted in its lower portions into a snow-drift glacier, or glacieret; and, in their excavations, the party cut across the junction between the snow and the ice, laying it bare for some 12 feet by 9 feet. It was then seen that the junction was by no means even, little tongues of ice running up into the snow. Above the actual junction, which was quite definite,

* Excellent examples of slip planes, made evident by lines of small crystals separating areas containing much larger ones, are figured by R. M. Deeley ('Geol. Mag.,' vol. 4, December, 1907).

the ice grain decreased gradually in size and became more névé-like (that is, with the air located between the grains). This névé again passed by imperceptible gradations into the typical stratified snow of the snow-drift. A section through the drift and the underlying glacieret is shown in Fig. 47.

Most typical glacier ice includes air in the form of small bubbles which, though it is not sufficient in amount notably to diminish the density of the ice, is quite enough to give the ice a distinct whitish tinge similar to the colour of lightly-frosted glass (Plate XCVII). In the Antarctic, indeed, all our observations point to the fact that transparent ice free from bubbles is due to the presence of water either

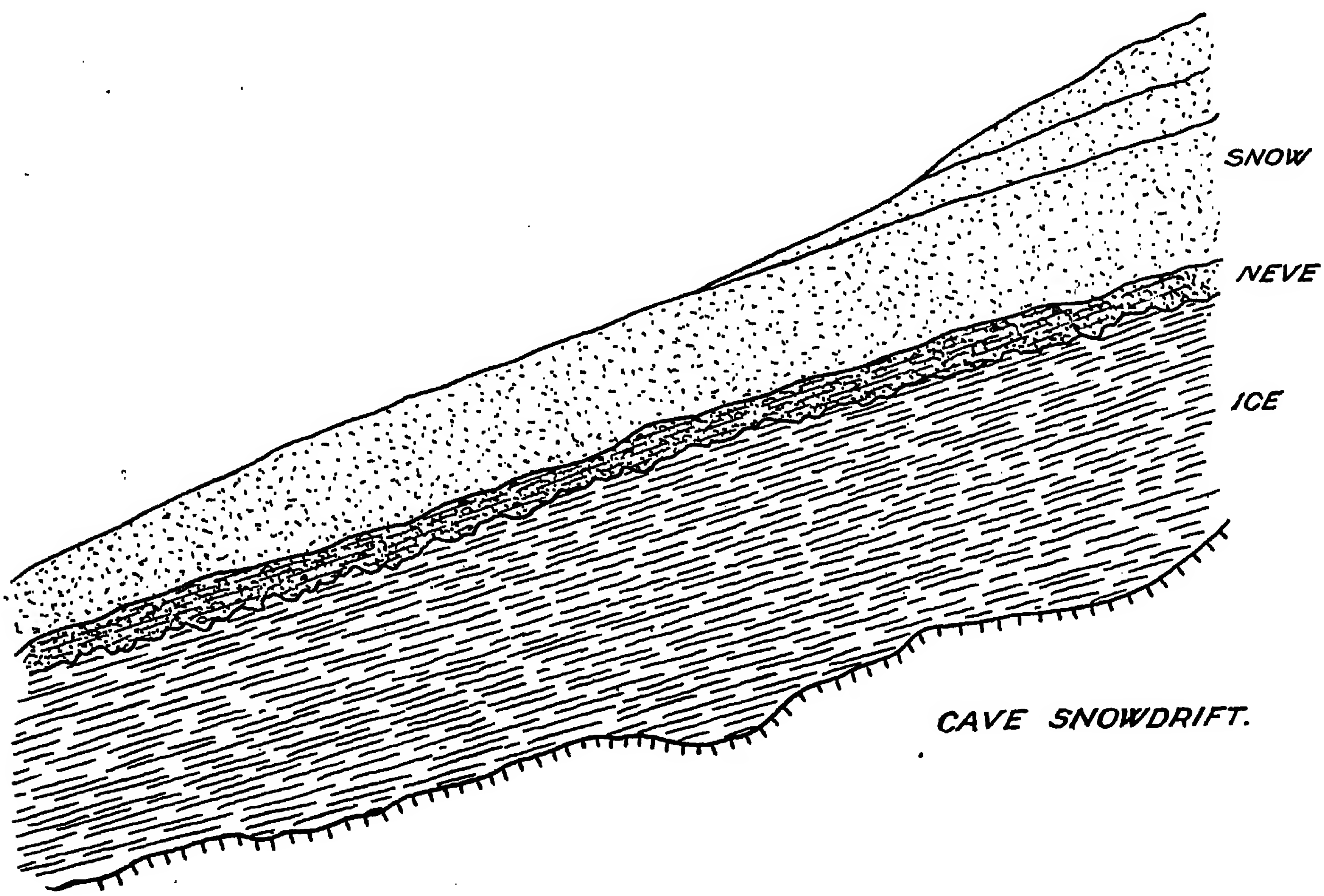


Fig. 47.

at the time of formation of the ice or later. A breccia of bubbly glacier ice in air-free ice is shown in Plate XCVIII.

In the cliff face of many of the glaciers which have come under our observation, bands and irregular areas of clear ice do occur, and their occurrence and method of formation are fully discussed in pp. 238–247, Chapter VII.

One way in which thin bands of blue ice of great extent might be formed and afterwards incorporated in a glacier has once or twice been indicated during summer thaws we have seen. Both on the Ferrar, and to a less extent on the Priestley Glacier, considerable stretches of the surface have been seen to be literally bathed in water for a day or two at a time, and a distinct change in the colour of the ice (from the whitish

frosted appearance presented by bubbly ice, to the darker greenish-blue of comparatively bubble-free ice) has been observed to accompany the thaw. In the cases which we have seen, it is improbable that this would have any permanent effect on the glacier, for it is likely that this surface ice would be completely removed by ablation before the next summer. If, however, we imagine a case when the summer temperature conditions remain much the same, but the snowfall is heavier and the glacier is increasing in thickness, it will be clear that the blue band produced by the process referred to above will have come to stay, and may later appear at the base of the glacier as a stratum of air-free ice.

If we now turn to smaller areas of blue ice on or near the glacier surface, we find that such areas do occur in great number, and that, in all cases where their cause is definitely known, they are directly due to the effect of standing or running water. The great majority of such air-free areas of ice are to be found in the neighbourhood of rock, either the rock sides of the glacier valley, or the rock of moraines carried within, or on the glacier. It is impossible to make a day's journey on the normal Antarctic valley glacier in summer without seeing such areas in process of formation, while in winter their origin is just as clearly betrayed by their position.

A good example of such an area was seen near the lateral moraine of the Koettlitz Glacier. Here the ice is covered by a thin veneer of morainic material, and must continually be subject to the influence of the thaw water formed in the summer. At the same time, it is protected by the same covering of rock from removal by ablation, and, therefore, is more persistent than in the cases before mentioned (Plate CXCIV).

Possibly, however, the best examples of such small areas of clear ice are furnished by those cryoconite holes which have at one time definitely contained water, but which have been emptied slowly by the water draining away through cracks in the body of the glacier. A section through such an empty cryoconite hole (see Fig. 48) shows how, during the period when the hole was filled with water, this had percolated into the surrounding ice-mass (of identical structure with the glacier ice), and had filled up the space formerly occupied by the air bubbles. In the result, that portion of the ice which was close to the cryoconite hole had been completely transformed, to a depth of 2 inches, into perfectly transparent ice.

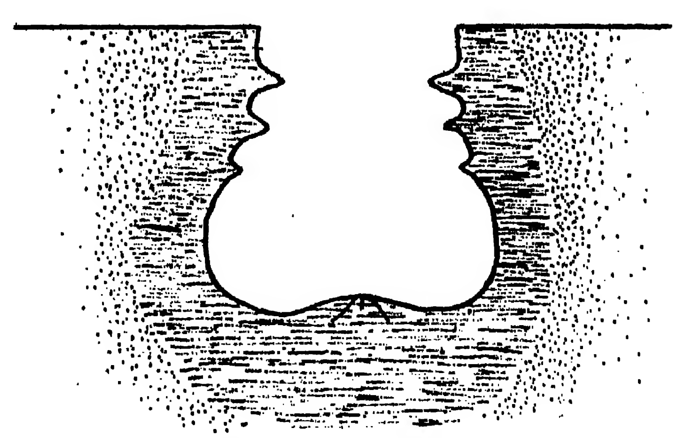


Fig. 48.—Vertical section of cryoconite hole, showing structure and area of water-bathed ice around it.

It is examples such as the foregoing which lend support to our view that many of the larger horizontal bands of air-free ice occurring in the Antarctic glaciers are formed by the action of water. The matter will, however, be more fully considered, and from a different point of view, in Chapter VII.

In the case of sheet ice formed directly on the surface of water, the amount of air present, and, therefore, the total amount included between the boundaries of the crystals, is practically fixed. If, however, the conditions change in any manner during the period of formation of the ice, or if the water surface is disturbed, the crystal structure becomes irregular, and the available air may be unequally distributed. It is indeed probable that the air temperature at the time of formation of the surface ice, and, therefore, the rate of freezing, has also something to do with the amount of entangled air. One case does, however, occur in which the amount of included air is notably greater than usual. This is the case of the freezing of a pond in which the water has been partly or wholly filled with drift or fallen snow to form a slush-like mixture. A considerable quantity of air is usually entangled in the snow, and, once a layer of ice has formed over the pool, this cannot escape, but must be included in the body of the ice.

Though, in the general case, the amount of air included in the ice is dependent on that which was present on its first formation, there are particular cases in which subsequent changes can occur. These modifications may make either for an increase or a decrease in the proportion of air in the ice, and occasions in which the presence of water causes a decrease in air-content have already been cited.

A change in the other direction also occurs in the surface ice of ponds or streams where, after the first formation of ice, the supporting water beneath has wholly or partly run off. The skin of ice in this case remains attached to the bank, and is curved, so that, at least at the sides, the ice is underlaid, not by water, but by air. Owing partly to the bowing of the ice covering whereby the individual crystals are slightly separated from each other, partly to changes of temperature and to draining action, and partly to the presence of a body of air beneath the ice, a much larger proportion of air is finally entangled between the crystals of the ice sheet. This action may proceed so far, indeed, that the crystals beome outlined on the surface by very definite white lines of width from $\frac{1}{16}$ inch to $\frac{1}{8}$ inch. The ice produced in this way we have called "arabesque ice," and it differs only in its mode of formation from the type referred to in the Shackleton Memoir as "prismatic ice."* It is quite commonly found at the edges of ponds which contain air below the surface ice, and which ring hollow to the blow of an ice-axe (Plate XCIX).

The form of the air bubble is dependent very largely on the method of formation of the ice, except in those rare cases when the bubble is formed in the ice at a later date. Thus, in the case of the ice formed on the surface of a confined body of water, whether salt or fresh, we have to deal with two different types of bubble. Bubbles approaching a spherical or elliptical shape occur within the body of the crystals, but a much greater proportion of the included air is squeezed out between the crystal boundaries in the form of tubes.† The diameter of these vertical tubes may be anything up to $\frac{1}{16}$ inch, and their length may vary from less than $\frac{1}{4}$ inch to 2 inches.

* British Ant. Ex., 1907–9, vol. i, 'Geology,' David and Priestley.

† *See* footnote to p. 75.

Both Drygalski and Mawson have drawn attention to the fact that the air tubes occurring between the crystals of lake and pond ice are usually hexagonal in horizontal cross-section. This is only to be expected from their occurrence at the crystal boundaries, and has been borne out by our own observations.

Quite commonly, those ponds which are completely frozen to the bottom contain bubbles of significantly greater diameter, and these are not filled completely with air, but with a mixture of air and granular ice exactly similar to some types of snow. These are the druses of the Shackleton Memoir.* Where the quantity of air is particularly large, as in the arabesque ice referred to above, it is no longer concentrated in threads, but shares the whole of the bounding planes between the crystals with this granular snowy deposit.

The presence of this snowy deposit within bubbles, and other air spaces within the ice, is best explained by reference to the changes of temperature which take place during the life-history of the ice. The temperature of the ice when first formed is, of course, in the case of ice formed from fresh water, 32° F. If we then imagine a fall of temperature of many degrees such as must take place on the approach of winter, the obvious result is the deposition of a certain amount of the moisture held in the air within the bubbles at the higher temperature. This deposition takes place apparently in the form of minute crystals on any prominences in the ice walls of the bubble, and, for some reason connected with the conditions within the bubble, the ablation which coincides with the next rise of temperature takes effect mostly on the ice of the walls and not on the fresh snow. An infinite number of small temperature changes within the bubble results, finally, in the growth of a significant deposit of finely-granular ice.

A curious type of bubble formation is seen in the ice of lakes whose bottom is covered with decaying vegetable matter, as, for instance, alga. The decay of this alga continues even after the surface of the lake has become frozen, and the gas generated during decay forms in bubbles which rise at intervals to the under surface of the ice. As the ice sheet thickens, the bubbles are frozen in, and, finally, the presence of the mass of decaying matter is indicated by a whole series of bubbles frozen into the ice above. The actual form of these bubbles is shown in section in Fig. 49. They are roughly of elliptical section and they increase in size as the depth increases. Like other types of air bubbles and tubes, they may contain a little of the ice powder before mentioned. The reason for the increase in size of the bubbles of this type with depth, is, undoubtedly, to be found in the rate of formation of the ice. The decay of the vegetable matter will naturally proceed at an almost uniform rate, and the gas will be given off as a constant stream of minute bubbles which will rise to the surface immediately above the decaying plant, and will there collect in

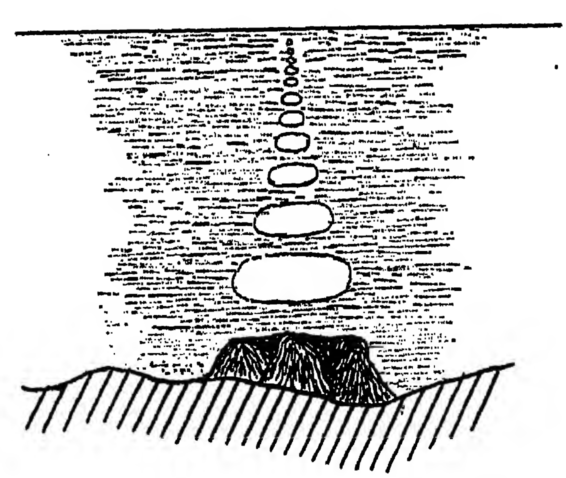


Fig. 49.—Showing method of formation of bubbles in ice due to decaying vegetable matter.

* British Antarctic Expedition, 1907–9. Vol. I. 'Geology.' David and Priestley.

larger masses. If the ice is forming comparatively quickly, as it is in the upper layers, only a few of these bubbles will be able to join up before the resultant air-body is surrounded and frozen in. As the ice becomes thicker and its formation therefore becomes slower, the bubbles frozen in will naturally increase in size (Plate C).

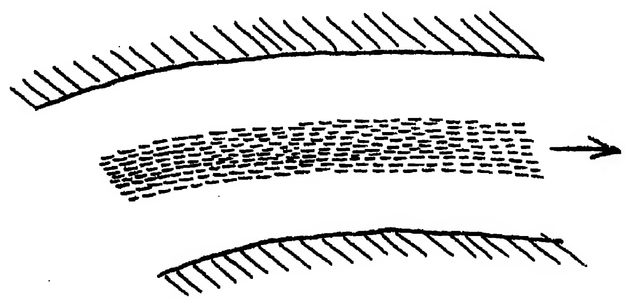


Fig. 50.—Lines of bubbles in a frozen stream.

Of unknown significance is an observation made on February 23, 1911. About noon on this day, on the route up the Koettlitz Glacier, a frozen stream was seen which was about 30 inches in width (shown in plan in Fig. 50), the centre of the stream being depressed about 1 foot below the bank. Towards the centre of this stream occurred numbers of drawn-out bubbles, and these were about $\frac{1}{2}$ inch across, with an average length of 1 inch, and were separated from each other by spaces of about 2 inches. They were commonly arranged almost end to end, in lines roughly parallel to the stream banks, so that they followed the original lines of flow in the unfrozen stream.

From the above discussion of the form of bubbles occurring in ice formed directly from water, it will be seen that the tendency is towards the formation of elongated bubbles, or strings of bubbles of quite considerable size. The case with ice formed directly from snow is, however, quite different. In this ice, the bubbles are never large—in general, less than $\frac{1}{32}$ inch in diameter—while the general form is spherical. They are also arranged in a haphazard fashion throughout the ice and, after the change from névé to ice is accomplished, they are quite independent of the position of the crystal boundaries. Glacier ice, therefore, instead of being transparent in patches, as is fresh-water ice on ponds, is everywhere translucent for layers of ice more than an inch thick. This ice, instead of being black like the fresh-water ice of lakes and ponds, is almost as white as the ice formed by the freezing of a mixture of snow and water. The light colour is evidently due to the light reflected from the ice-air surfaces within the ice.

It is, however, easy to see that air will be locally present wherever fine cracks have been formed by contraction on decrease of temperature, or from movements within the ice, since, even if the cracks close once more, they will not do so exactly. A certain amount of air is thus imprisoned in a plane which may run in any direction from vertical to horizontal. Where these planes cut the glacier surface or glacier front they will invariably show up as fine lines of bubbles running continuously, sometimes for considerable distances.

Mention should be made of the fact that the first sign of a thaw on a glacier surface is the sizzling sound due to the escape of the bubbles in the ice through the water-film on the surface. Quite evidently this air is included in the ice under pressure (at least at melting temperature). Further evidence of this is afforded by an observation

made, at Cape Adare, on a block of ice which had been brought into the hut and had been slowly brought to the melting temperature. It was found that, under these conditions, many of the bubbles within the ice became surrounded by a layer of water so that, on moving or shaking the block of ice, the bubbles were themselves displaced. This melting may be due to the pressure exerted by the bubble, or possibly to unequal absorption of radiation ; the important fact is that the ice in the immediate neighbourhood of such bubbles is more prone to melt. We would, therefore, expect that, in such ice, the tendency would be for the bubbles to assume the spherical shape. As mentioned above, this is the general rule for bubbles in glacier ice, while the size of the bubbles in any sample of such ice is exceedingly regular. We have also seen that the amount of included air will probably be dependent on the rate of change of the snow into glacier ice, and on the subsequent meteorological conditions in promoting or preventing the formation of thaw water—that is, dependent on the temperatures of the region where the glacier is formed and moves. Even the most casual glance at the glacier ice of the South Victoria Land region enables one to see that the amount of included air is here much greater than in the Swiss Alps, or in the Southern Alps of New Zealand. We have even thought that the glacier ice in the Cape Adare region is in general clearer than that in the McMurdo Sound portion of the Continent, but this is merely an expression of opinion which should carry but little weight. It is, however, fairly certain that the presence of transparent glacier ice in the Antarctic (whatever the amount of air included in large bubbles) is an unfailing indication of the presence of water, either at the time of its formation, or during the period which has since elapsed.

This brings us to one of the most interesting points connected with the subject of Glaciology. We have noted, not once but several times, that horizontal planes of rather more transparent ice in a glacier terminal or lateral face contain quite often, a small amount of very finely-divided silt, and also show a definite elongation of the bubbles in their vicinity (Plate CI). The connection between the dark silt and the greater transparency is easily understood ; though it is not so simple to determine whether the silt has been carried there by water percolating from above, or whether the absorption of radiation by the silt has been the cause of the formation of the water and, therefore, of the greater transparency of the layer of ice. This will be discussed fully in Chapter IX, under the heading " Silt-bands."

In general, asymmetrical air bubbles are only to be found within a few inches of the transparent layer, though examples are not entirely wanting of its occurrence at greater distance (Plates CII and CIII). The bubbles are apparently elongated parallel to the direction of movement of the ice (in the planes parallel to the silt-bands), and have a length 1½ to 2 times their breadth. From the regular structure of normal glacier ice containing spherical air bubbles, it seems probable that this asymmetry must be connected with the occurrence of the transparent silty layers. From the coincidence between the direction of the major axes of the air-tubes and the direction of glacier flow, it seems probable that the elongation of the bubbles in any horizon is associated with

differential movement in that plane. In some degree this is evidently analogous to the formation of elongated bubbles in ice on a stream surface, as described on p. 114.

Just as the inclusion of air bubbles in the separate glacier grains is an indication of the change from névé to ice, whereby the air around the névé grains is transferred into the interior of the ice grains during growth, so also the occurrence of lines of bubbles within the grain is often an indication of the former position of a crystal boundary or crystal boundaries. Plates CIV and CV show compacted snow and névé, which should be compared with Plate XCVII showing normal Antarctic glacier ice. Particularly striking is the development which is to be found in the ice covering many of the cryoconite holes. When the water first freezes in these holes, a surface layer of clear blue ice is formed. The air is not included within the crystals, but is extruded at the boundaries in such manner as to form long air-tubes about $\frac{1}{10}$ inch in diameter. Owing to the fact that the formation of the ice proceeds by conduction from the walls inwards, a peculiar radial arrangement of the crystals takes place, and this is well shown up by the crystal boundaries.

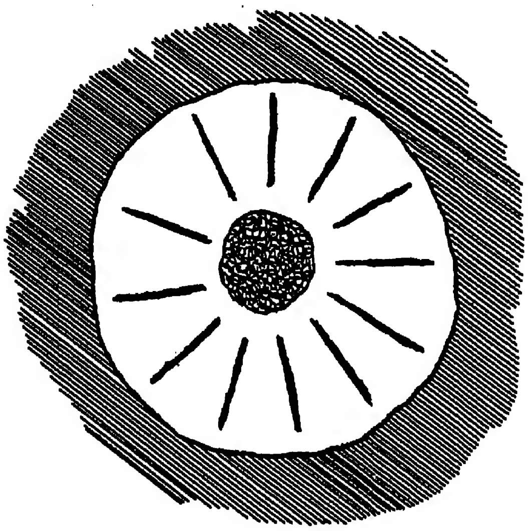


Fig. 51.—Arrangement of air tubes in a cryoconite hole (horizontal section).

Fig. 51 shows one of the common methods of arrangement of the air tubes, which do not generally meet in the centre, but merge together as a bubbly core. These radially disposed crystals are quite commonly three inches in length. In a very large number of cryoconite holes, a test with the polariscope shows that the bubble lines and the crystal boundaries are the same, but in many others we have found that the clear ice in the cryoconite holes has the same granular structure as the clear ice near by, the granules being independent of the arrangement of the bubble planes. There seems, therefore, no escape from the conclusion that the simple radial structure of the first formation may be modified in the course of time into a granular structure of the normal glacier type. Mention of a similar change in the ice of "filled" crevasses has already been made.

The most important factor in its bearing on the amount of included air is obviously the temperature, for we have already seen that the presence of water is able to free the ice completely. The scarcity of blue glacier ice in the Antarctic is, in fact, the very best testimony to the rigour of the Antarctic climate. The high air-content of the Ross Barrier and other similar formations, when compared with that of normal glacier ice, suggests that, even where water cannot exist, the density of ice will vary greatly with the temperature during formation. Though true glacier ice has been described as possessing a distinct whitish colour, comparable with that of lightly-frosted glass, it must not be thought that the total amount of included air is very large. To test this point, a single observation for the density of white glacier ice was made. This was very

simply and roughly done by dropping a large piece of melting ice unto pure alcohol at a temperature a degree or so above the melting-point of ice, and allowing it to dissolve and form a mixture of greater density. The piece of ice was removed as soon as sufficient was dissolved in the alcohol to cause the ice to move towards the surface of the solution. The density of the solution was then taken as that of the ice at 0° C., and was determined by direct weighing in a specific-gravity bottle. The result showed the density of the sample to be 0.897. By comparison with the density of pure ice given in Table XX of the Appendix, we see that the amount of included air in this sample of glacier ice was only about one-fortieth of the whole volume. A similar observation for the density of the surface layer of sea ice gave the value 0.924.

CHAPTER IV.

THE MECHANISM OF GLACIER MOTION.

For very many years, the explanation of the movement of glaciers from their gathering grounds at high altitudes to the lower levels where denudational forces predominate has exercised the minds of glaciologists. The motion of the glacier has been ascribed in turn to many different causes. Of the numerous theories which have been propounded, that which has probably the greatest number of followers ascribes the motion of the glacier to the melting of ice which takes place under pressure, at a lower temperature than the melting-point under normal atmospheric pressure—to this, and to resultant actions that follow from this melting.

As is pointed out in a later chapter, the study of Glaciology has been, in some measure, handicapped by the fact that the area of investigation of the early glaciologists was restricted to those portions of the earth which were most easily accessible to them, *i.e.*, primarily to mountainous regions in temperate zones. As a result, the earlier theories of glacier motion were framed to fit a set of facts applicable to only a few types and sub-types of glaciers. Any complete theory which is to apply to all types of glaciers must correlate a much larger number of facts, and must, therefore, be of a very general nature.

It is not intended in this Chapter to elaborate a theory which will apply to all types of glaciers under all possible conditions, but merely to indicate a generalization which we think is of fundamental importance, observing at the same time that many of the older theories of glacier motion are, to some extent, valid; or, in other words, that the motion of a glacier is due to several causes each operating in its own particular sphere.

In the opinion of the writers, an important cause of glacier motion in temperate regions is the lowering of the melting-point of ice under pressure, such as melting at the points of contact between individual ice crystals in the upper levels of the glacier, the water flowing to positions of less pressure. This must be combined with two other facts :—

(1) The tendency for the crystals to grow in average size, and

(2) The fact that increase of pressure produces a rise in temperature.

As regards the increase in mean size of the crystals, this, as has been pointed out by Chamberlin,* should be carried out through the growth of the larger crystals at the

* T. C. Chamberlin, 'A Contribution to the Theory of Glacial Motion,' Decennial Publications, University of Chicago, Series I, 1902, "Geology."

expense of the smaller ones, this action taking place for the reason that the average vapour pressure over a small crystal is greater than that over a large crystal.

Several passages in Chamberlin's treatise are, however, obscure. Thus, the increased vapour pressure over a small crystal is said to be due to the increased curvature of the surface as is the case with water-drops. ". . . Another factor that enters into the process is that of pressure and tension. The granules are compressed at the points of contact and put under tension at the points not in contact; and the pressure and tension are, on the average, likely to be relatively greatest for the smallest granules. Tension increases the tendency to evaporation, and adds its effects to surface curvature. The capillary spaces adjoining the points of contact probably favour condensation . . . ." The statement that tension increases the vapour pressure is not clear; it is a fact that vapour pressure is increased by *increased* hydrostatic pressure.*

When we come to consider the motion of the large glaciers which are found in polar regions, we at once recognise that in many respects the explanation given by Chamberlin is insufficient. Thus, the lowering of freezing-point is only about 3° C. for 400 atmospheres pressure, so that the thickness of a glacier would have to be about one mile before the melting temperature at the bottom was generally lowered by 1° C. Melting and transformation of the ice to water we can be certain *never* takes place in the main mass (below the surface layers) of the immense land glaciers of the Antarctic Continent, however large a part this process may play in the mechanics of glacier motion in more genial climes.

It appears to the writers that the fundamental cause of glacier movement in cold regions, where water is never seen except in the immediate neighbourhood of rock, depends on a property analogous and additional to the vapour pressure of ice.

A growth of large crystals at the expense of small ones may be due in part to a greater vapour pressure over the latter; the increased vapour pressure under increased hydrostatic pressure will cause the movement of vapour from points where crystals are pressing against one another to points where they are not in contact; an increase in pressure will produce a momentary rise in temperature at those points where crystals come into contact, which may result in an increased vapour pressure; these actions are all referable to the physical property known as vapour pressure, and this property seems to be sufficient to explain many of the changes that occur in a glacier. In low latitudes, where the temperature in the body of a glacier approaches 0° C., the formation of water between the individual crystals may result,† and the changes in the glacier will, in this case, proceed with much greater velocity.

First, it seems desirable to point out some consequences of Chamberlin's simple conception that the changes within a cold glacier may primarily be referred to the individual

* Chamberlin also states that the internal heat from the earth is sufficient to melt ¼ inch of ice per year, and suggests that this heating, considered in connection with the lowering of melting temperature under pressure, is sufficient to keep the lowest layers of ice at melting-point.

† This takes place when the vapour pressure of the ice at the temperature and pressure in question rises to the vapour pressure of water at the same temperature and pressure.

vapour pressures of the separate crystals. Approaching the matter from the physical standpoint, one may first of all consider the case of a single perfect crystal in equilibrium with its vapour pressure. For each face of the crystal, the number of ice molecules passing from the crystal to the atmosphere surrounding it must be equal to the number entering the face of the crystal, this number being conditioned by the vapour pressure. Following Todd's* conception, all molecules striking the surface enter the crystal, while only those molecules which have a velocity or energy exceeding a certain value† can leave the crystal.‡ The crystal loses a certain amount of energy with each molecule which succeeds in escaping from the crystal, and this loss of energy is associated with the latent heat of vaporisation of the molecule. It is useful here to follow Dieterici in his conception of the solvent pressure which acts in the interior of a liquid. This solvent pressure cannot be measured directly, since any direct measurement involves the production of a surface of discontinuity. Within the liquid, however, the solvent pressure is a true bombardment pressure which will follow the ordinary gas laws. This bombardment pressure is very large and the observed boundary pressure (vapour pressure) results therefrom.

It is usual to look on the total energy in a liquid as made up of two parts, one proportional to the volume and the other proportional to the surface. The average energy per molecule in a large crystal should, therefore, be less than that in a small crystal and, in the absence of any other source of energy (for instance, electrical or mechanical), molecules should be transferred from the small crystal to the large, so long as the vapour can pass from one to the other and whether the crystals are touching or not.

As the vapour pressure increases with temperature, so also will the rate of growth of the large crystals at the expense of the small ones, other things being equal. This is a well-known fact which has been many times noted in the case of ice, and was the subject of special experiments by C. E. Peet and E. C. Perisho,§ under the direction of Professor Chamberlin.

Experiments have been carried out,|| which prove that the rate of growth of crystals increases with pressure, as we should expect from the fact that the vapour pressure increases with hydrostatic pressure. In most of the experiments, however, the growth has taken place at freezing-point. It would seem, therefore, that the increase in mean size during a given period must be conditioned chiefly by the temperature, the vapour pressure being much more sensitive to temperature than to pressure variations.

The conception outlined above might be held to account for the movement of glaciers at temperatures well below freezing-point, but it is necessary to point out an

* G. W. Todd and S. P. Owen, 'Phil. Mag.,' vol. 38, November, 1919.

† More plausibly, only those molecules having a velocity of translation perpendicular to the surface exceeding a certain value. *See also* Bennewitz, 'Ann. der Phys.,' 1919, No. 11.

‡ *See* footnote to p. 50.

§ Chamberlin, *loc. cit.*

|| *See* Appendix.

apparently fatal objection to the conception, viz., that the velocity of glaciers and the rate of growth of crystals in mean size at temperatures just below freezing-point appear to increase very greatly as the melting temperature is approached, the increase of vapour pressure with temperature at this portion of the temperature scale being much too insignificant to explain the effect.

It is important to note in this connection that Professor E. C. C. Baly's investigations* suggest that the latent heat of evaporation should approximate to the amount of energy associated with a change of phase—that is to say, one or more energy quanta at the infra-red fundamental frequency, for every molecule. In the case of water, two quanta appear to be associated with this change. The latent heat of fusion should equally be associated with a change in the number of quanta of energy associated with each molecule, and it is difficult to escape the conclusion that, since a certain number of water molecules at any temperature possess sufficient energy to enable them to escape from the liquid into the vapour above, so also a certain number of molecules of ice will possess sufficient energy to escape from the ice into the vapour form, while a much larger number of molecules will possess energies sufficient to enable them to exist in a " liquid " phase. Just as the molecules in water (when the temperature is raised to the critical point) can only exist in the vapour form, so also ice molecules cannot exist as such above the triple point.†

Todd's equation agrees fairly well with the observed vapour pressure of water at various temperatures and, as one would expect, the increase of vapour pressure with increase of temperature rises rapidly as the critical temperature is approached. It seems, therefore, reasonable to regard ice at any temperature as a mixture of three molecular phases. One of these phases consists of " vapour " molecules with sufficient energy to enable them to escape from the solid to the vapour, and in number conditioned by the vapour pressure of the ice at that temperature. A second phase consists of " liquid " molecules of less energy-content (though still greater than a critical value), sufficient indeed to afford them a certain mobility within the ice. The third phase

* 'Phil. Mag.,' vol. 40, July, 1920.

† Clearly, the simple empirical relationships which exist between such constants as latent heat of vaporisation, critical temperature, fusion temperature, boiling point, etc., have a real physical significance. Cederberg ('Phys. Zeit.,' xiv, 829, xv, 699) has discussed a formula connecting the vapour pressure of ice with the temperature, and suggests that this relationship can be expressed as a function of the ratio-temperature/critical temperature, which is of the same form for all substances, only the constants differing. The fact that a solid cannot exist above the triple point, or a liquid above the critical temperature, is significant, and suggests that when the mean molecular energy reaches certain values, changes take place which are of the nature of a redistribution of the energy. Point is lent to this view by the discovery of Borelius and Gunneson ('Ann. der Phys.' lxvii, p. 227) that the thermo-electric force of tungsten and iron experience periodic changes at absolute temperatures which are an integral number of times a certain constant. It is reasonable to suppose, as does Borelius, that a sudden redistribution of energy takes place in the solid phase at these temperatures, when a certain fractional part of the atoms possesses a number of quanta equal to or greater than a new integer. (*See also* 'Nature,' 109, p. 613.) The " mobile " (liquid) molecules we have postulated will be all those molecules possessing more energy than that corresponding to a certain number of quanta; and the melting point will be the temperature at which a redistribution of energy among the molecules takes place.

consists of " ice " molecules possessing still less energy—insufficient energy to allow them to move far from their positions of rest. Just as the number of vapour molecules in water increases greatly as the critical temperature is approached, so also should the number of " liquid " molecules in ice increase greatly as the triple point is approached. If we are right in conferring upon these " liquid " molecules a mobility between that of the vapour and the solid, an explanation is afforded of the great increase in velocity of glaciers as the melting temperature is approached.

Unfortunately, we have no experimental means of verifying this idea, or of making evident the presence of the mobile molecules in ice, if indeed they have a real existence. It should be pointed out that this conception involves the existence of a bombardment pressure within ice similar to that postulated by Tinker as existing within a liquid. Where ice is in equilibrium below freezing-point with a solution such as sea water, this equilibrium can only be due to an equivalent motion of water molecules into and out of the ice. According to Tinker, the bombardment pressure of a solution is lower the higher the concentration of the solution, and it seems reasonable to assume that the bombardment pressure in the ice will also be less the lower the temperature. The bombardment pressure in a solution is increased by application of external hydrostatic pressure, and becomes equal to that of pure water when a pressure equal to the osmotic pressure of the solution is applied. In the case of ice, also, the application of hydrostatic pressure should increase the number of mobile molecules and, therefore, the bombardment pressure, and, when sufficient pressure has been applied to melt the ice, the bombardment pressure should be equal to that of pure water. The pressure required to liquefy ice is therefore a pressure somewhat analogous to the osmotic pressure of a solution, ice being looked on as a " solution " of ice molecules in water molecules.

The analogy seems so complete that we are probably not very far from the truth in treating the hydrostatic pressure required to liquefy ice as the osmotic pressure of ice at that temperature, and in regarding this pressure as roughly proportional to the number of " ice " (immobile) molecules present in the solid.

As pointed out before, it is not possible to test the correctness of these views, but there can be no reasonable doubt that they enable one to form a fairly coherent picture of the mechanism of glacier motion. The main features of the conception are—a notable increase in the number of " mobile " molecules as the triple point is approached, and a rigid framework of " immobile " molecules. These conceptions are sufficient to explain the great increase in glacier movement and increase in the rate of growth of the crystals as the triple point is approached, either by increase of temperature or of pressure, and also the rigid character of ice at temperatures much below the freezing-point. The movement of molecules will be from regions of high potential energy to regions of low potential energy, *i.e.*, generally downhill. It is important, however, to emphasise that the idea of mobile molecules in the rigid ice lattice does not demand that those molecules which are mobile at one instant shall always remain mobile : owing to collisions with the immobile molecules, there will be a constant interchange of mobility from molecule to

molecule. The crystal lattice itself will move as a result of this interchange and will carry with it, in its motion, all the superincumbent layers of ice.

It is not possible to calculate the coefficient of viscosity of ice from the data which are available, but it seems probable that the frictional resistance to motion of the "water" molecules will be some function of the number of ice molecules present. In any case, we will expect the velocity of flow of ice under pressure to be some function of the temperature-difference from the triple point, the value of the function being low for low temperature and rising rapidly as the triple point is approached.

In the light of these remarks, it appears that the simple conception of vapour pressure as the prime cause of glacier motion is insufficient to account for the facts, though no doubt this method of molecular movement plays its part—a part which may well be of great importance in the earliest stages of the growth from snowflakes to glacier grains, when the grains are separated by air spaces. A deduction which holds equally on either view is that temperature changes will be of greater importance in modifying the rate of movement of the ice than the pressure *changes* which are usually existent in actual ice streams. As pointed out before, the weight of ice a mile in thickness is equivalent in its effect to a rise in temperature of about 1° C. The comparatively high rate of movement associated with the Ross Barrier is no doubt due to the comparatively high temperature of the lowermost layers, which are laved by the sea.

We see then that the snow falling on the gathering ground of a glacier will grow in size to névé grains* at a rate chiefly dependent on the temperature. As the névé grains grow in size, the air previously included in the mass between them is now found within the individual crystal grains, this process taking place by the extension of certain crystal boundaries, the presence of included air being in no sense necessary for growth to proceed. The glacier grains, like the snowflakes from which they have originated, have their axes oriented in all directions, so that changes in the crystal boundaries will continually take place, the movement of the boundaries being simply the expression of the transfer of molecules from crystal to crystal. By the application of local pressure or strain, the average energy per molecule and the proportion of "mobile" molecules at certain points will be locally increased, and the molecules will move from these points to points where the pressure is less. Other conditions being equal, the rate of wander of the molecules should be roughly proportional to the pressure gradient, the total movement of ice being also conditioned by the number of "mobile" molecules which are present.

There is some experimental evidence that the "viscosity" of ice differs in a single crystal along the different crystallographic axes.† This difference is possibly referrable to the fact that the distance between ice molecules differs along these axes,‡ and it is reasonable to assume also that the frictional forces exerted on the "mobile" molecules

* Névé being defined as that condition of ice when the air included in the ice lies between the boundaries of the crystals.

† McConnell, 'Proc. Roy. Soc.,' March, 1891.

‡ Dennison, 'Phys. Rev.,' vol. 17, January, 1921.

will also differ for movement along the different crystallographic axes. It is not impossible that the tendency reported from time to time towards a regular orientation of the glacier grains near the terminal face of a glacier may be associated with the direction of the greatest pressure gradient in the glacier. As to whether the mean size of the glacier grain will have any direct effect on the rate of movement of a glacier, it is impossible to say.

It is now necessary to consider in some detail the question of the growth in mean size of glacier grain and its relation to the existing temperature and pressure conditions. We do know that the growth in mean size of the glacier grain in the course of time is in some way related to the temperature and pressure, but no exact figures are available. In lower latitudes, the mean size of the glacier grain* is large in comparison with the mean size in Antarctic glaciers, and, in the Antarctic, the mean size in those portions of the glacier which it is known have experienced higher temperatures is greater than elsewhere. No tendency has, however, been observed to an increase in mean size of glacier grain at high pressures (great depths) in Antarctic glaciers.

So far as we are aware, no theoretical explanation of the causes for such growth has been discussed, nor is this memoir the place for a discussion of this nature. It does seem desirable, however, briefly to indicate a possible explanation for the growth of ice grains in a glacier, somewhat on the lines of the conception propounded to explain the movement of the glacier as a whole. In this, we must look on each glacier grain as a unit by itself, containing for a given temperature and pressure a certain number of " fixed " molecules and a certain number of " mobile " molecules. The latter would comprise all molecules possessing sufficient energy to enable them to escape from one crystal into an adjoining one, and it seems probable that the number of molecules of this nature will depend on the temperature, on the pressure, and possibly also on the orientation of the crystallographic axes relative to those in the adjacent crystals.

For an ice crystal in equilibrium with its vapour, we recognise that only a small number of molecules have sufficient energy to pass the boundary from ice into air, while a larger number have sufficient energy to reach the boundary. We may therefore look on the surface of such a crystal as the place where certain high-energy molecules are to be found and the vapour around as the place where still more highly-energized molecules exist. Small grains of high mean molecular energy should therefore disappear and the large grains grow at their expense.

In a single crystal, we can look on the whole energy as made up of two parts—one, due to the fixed ice molecules, and one due to the mobile molecules. The former are fixed in mean position, while the latter can move to the boundaries of the crystal and pass the boundary into an adjacent crystal. Clearly, if the surface energy of the crystal is different for the different faces, the number able to pass the boundary will depend on the orientation of the crystal relative to the adjacent crystals. Further, it is important to note that the surface energy is some function of the number of mobile and immobile molecules—such that, when the number of mobile molecules capable of

* Figures are given in a preceding chapter, page 104.

leaving the crystal is a minimum, the surface energy is a maximum, and *vice versa*. In the case of a liquid and its vapour, the surface energy is zero at the critical temperature θ_c, and, at another neighbouring temperature θ, the surface energy is proportional to $(\theta_c - \theta)$.

By analogy, we would therefore say that the surface energy at the boundary of two crystals in contact will be measured by the difference in the mean molecular energies of molecules in the two crystals, which will be conditioned by the number of mobile and immobile molecules in each.

It is not difficult to see that, as in the case of water-drops, the surface energy becomes of greater and greater relative importance the smaller the ice crystal. Just as the smaller water-drop must have a higher average energy per molecule, evidenced by the greater vapour pressure at any given temperature, so also must the smaller ice crystals possess a greater mean energy per molecule and a greater proportion of the mobile molecules. The movement of molecules must therefore be away from the smaller crystal and into the larger. This gives a possible explanation for the growth of large crystals at the expense of small ones, though the effect will be less and less important the larger the crystals become.

A complication is, however, introduced by the fact already alluded to—that the glacier grains have axes oriented in all directions, so that the total surface energy over any crystal boundary depends, not only on size, but also on orientation. In a glacier, the condition of equilibrium between crystals at any temperature is obviously that the mean energy of a molecule in each crystal shall be the same, and growth of some crystals at the expense of others will continue until this condition is attained. (In practice, the temperature changes and strains produced constantly within the glacier prevent the attainment of equilibrium.)

If the mean energy of molecules in a crystal is greater the smaller the crystal, it is clear that the rate of disappearance of a small crystal surrounded by larger ones will be greater the smaller the crystal which is in process of disappearance, and the greater the disproportionality in size. We would thus expect, as is found to be the case, that the disappearance of the smaller crystals will proceed much faster the smaller the mean size, and that the growth will become very slow when the crystals attain a moderate size.

Since the effect of increased temperature is to increase the number of molecules which have sufficient energy to reach the boundary from within an ice grain, this should result in an increased rate of growth in mean size of the glacier grains. The effect of increased pressure on one crystal only will clearly be an increase in the mean energy of molecules in this crystal and this will result in its quicker disappearance.

Observation shows that the rate of disappearance of the smaller crystals is somewhat accelerated at temperatures approaching the melting-point, and that the mean size attained is greater the higher the temperature. The relative increase in mean size seems to be, however, less than the relative increase in the rate of movement of a glacier as the temperature rises, which we have already explained as due to the large increase in the number of " mobile " molecules as the temperature increases.

In considering the question of growth in mean size, it is important to note that Antarctic observations lead to the view that, even at quite low temperatures, consolidation of snow to ice proceeds at a greater rate when the snow has been compacted by pressure, and we may legitimately consider this as an indication that growth proceeds more quickly when crystals are in closer contact, *i.e.* when the molecules can move from crystal to crystal directly without assuming the vapour phase. Considerations advanced in the next paragraphs based on the growth of crystals in strained metals provide, however, an alternative explanation.

The conception outlined above leads naturally to the corollary that, if additional energy is stored in certain of the glacier grains, so as to increase the mean energy per molecule in those grains, an additional reason for the growth of neighbouring crystals at their expense is provided. The mechanism is, however, the same. If, for example, certain crystals have been subjected to excessive strains, the possibility clearly exists that these strains, by increasing the mean energy-content of the molecules, may lead to molecular readjustments and to the disappearance of the glacier grains so strained.*

The conception outlined in the preceding pages must, therefore, be examined in the light of information derived from a study of strained metals. The paper by Professor H. C. H. Carpenter† summarises the greater part of the information which is available regarding the growth of crystals in metals. The first point to notice is that growth does not take place among the crystals formed in cast metals, no matter how small the crystals may be, as a result of rapid cooling through the temperature of solidification. On the other hand, crystals of metals which have been cold-worked or deformed show considerable modifications after annealing, depending on the degree of working and the temperature of annealing. Provided annealing is sufficiently prolonged, it is found that a deformation which is just sufficiently great to cause growth in the mean size of the crystal results in the formation of crystals of the maximum size. Smaller deformation followed by annealing leaves the metal unchanged, while large deformations result in the production of crystals smaller than the maximum size (obtained for a less deformation), and decreasing in size as the amount of previous deformation is increased. This decrease is claimed to be due to the birth and subsequent *growth* of new crystals in the boundaries between the old, the number of new crystals so formed being greater the greater the deformation. The maximum crystal size corresponds to the maximum deformation which can be given without the birth of new crystals. The maximum mean size attained for any deformation decreases as the temperature of annealing decreases, but is dependent solely on the temperature of final annealing when this is sufficiently prolonged. Finally, the rate of growth to the maximum size is quicker the higher the annealing temperature.

* The view here advanced seems to require that the effect of pressure, which is not hydrostatic, upon a single ice crystal will be to cause movements of the molecules of high energy-content and a permanent change in the shape of the crystal. It also seems to demand that the vapour pressure, latent heat of vaporisation, thermal conductivity, and other physical properties of ice will depend on the size of the grains composing the ice mass and the amount of work done upon it.

† 'Journ. Inst. of Metals,' No. 2, vol. 24, 1920.

These results are of considerable importance. They suggest that the strains experienced in glacier ice by its movement, and particularly in the passage past obstructions on its way to lower levels, should result in growth of the glacier grain at temperatures close to the melting-point, or, for greater strains, might result in a decrease in the mean size of the crystal as the result of recrystallisation. It may thus be the operation of this factor which limits the size attained by glacier grains at any temperature.

In the normal course of events, the glacier grain is continually being subjected to varying temperature and varying pressures, and if "annealing" takes place in this range of temperature, an analogy is afforded to the behaviour of metals. Is it this action then which is the cause of growth in mean size of the glacier grain, or is the theory already outlined sufficient to explain the facts? We think that the mechanism is the same in both cases; in other words, that, in the absence of sufficient deformation to produce recrystallisation, the effect of strains and stresses on the glacier grains is to alter the mean energy of the molecules in the different grains in such manner that growth of some takes place at the expense of others. It may well be that, in the case of metals, the effect of cold work upon the metal greatly exceeds the effect of "size difference" in promoting growth; but the fact that large ice crystals in air grow at the expense of small ones, when no strains can have been introduced, argues that the same effect is also operative in solid ice when the crystals are in contact.

It seems necessary to call upon the deformation theory for an explanation of the change (several times observed) from clear ice, obviously formed from water in a glacier crevasse,* into glacier grains similar to those in the white bubbly ice forming the main body of the glacier. The presence of small grains in narrow longitudinal veins which were obviously slip-bands are best explained as the result of recrystallisation, but might equally be due to snow drifted into cracks formed by a decrease of temperature.

As in cast metals which have not been subjected to strain, so also in ice formed from water, there is no evidence that increase in the mean size of the crystal takes place; but it must be remembered that ice crystals so formed are already of such dimensions that growth due to "size difference" could hardly be expected. Information on this point could, however, probably be obtained by the observation of ice quickly frozen in liquid air. We would in any case hardly expect quite the same growth in ice formed from water as in ice formed from snow-flakes. In the first case, equilibrium must exist between each crystal and the water from which it is formed throughout the freezing process, that is, the mean molecular energies throughout each crystal must be the same, being conditioned by the equilibrium with the water from which they are formed. It is, therefore, only when the water-formed ice is strained that one would expect the equilibrium between crystals to be upset and growth to take place. For ice formed from snowflakes, both the size and the orientation of flakes is more or less haphazard, and equilibrium will at no stage be possible, since growth means readjustment of strains. Readjustment of strains further alters the conditions and leads to

* Chapter III, p. 109.

further growth. The effective limit of growth might be set when the grains have reached a certain mean size, but equally might be set by the tendency towards an increase in the number of crystals caused by excessive mechanical forces which operate within the body of a glacier.

It is difficult to imagine the passage of a normal glacier from its gathering grounds towards the sea, without the local production of such strains as must cause recrystallisation, and (on the analogy of cold-worked metals) the consequent formation of smaller and more numerous glacier grains at the points of greatest strain. Results of this nature should be observable in favourable situations, but, with the single possible exception noted above, as occurring in longitudinal slip-bands, we have found no such effect. Such phenomena, however, would only be observed if growth due to " size difference " were comparatively slow. The fact that no record is available relating to a decreased size in glacier grain at the snout of a glacier (the grains in which have travelled farthest and been subjected to the greatest strains) is some evidence that, in ice, growth proceeds as a result of " size difference," as well as a result of strain.

If, in spite of the considerations which have been advanced above, it should be proved that crystal growth cannot take place without work having previously been done on the granular mass, we think it will be found that the mechanism of growth of the glacier grains will still be very closely associated with movement of the glacier.*

The theory of glacier movement outlined in the previous sections is of a general nature, and the conclusions apply to a mass of ice of uniform thickness lying on a horizontal plane, *i.e.*, the mass moves outwards in whatever directions its motion is least impeded. In the majority of cases, a glacier lies on sloping ground, the direction of movement being then largely determined by the direction of greatest slope. Though

* Since the above was written, our attention has been drawn to Sir George Beilby's publication (' Aggregation and Flow of Solids,' Macmillan, 1921). Beilby, dealing in Section VIII with the flow of ice in glaciers, states that ice which has been converted into the " vitreous " condition by flow immediately tends to return to the crystalline condition, even at a temperature so low as — 12° C. It is probable that the " vitreous " condition is only permanent at a still lower temperature. Beilby advances weighty arguments to prove that surface flow takes place at ordinary temperatures in the process of polishing metals and even glass, the surfaces so treated remaining in the " vitreous " condition of high energy-content, whose properties differ notably from those of the more crystalline mass below. On annealing, the surface again becomes crystalline. The mental picture offered of the vitreous state is that of solid molecules fixed in haphazard orientations, but rotating into crystalline order when heated above a certain temperature. The molecules in the vitreous condition possess a high potential energy and must clearly lie in the boundaries between crystals, if present within the mass of the solid. The vitreous condition may be induced by mechanical work, or sometimes by quick freezing, and is stable below the temperature in question. The metal in the vitreous condition is harder than in the crystalline state. The articles by Jeffries and Archer in the February and March numbers, 1922, of ' Chemical and Metallurgical Engineering,' and in the ' Journal of the Institute of Metals,' March, 1922, by the Research Staff of the General Electric Company, have since appeared and should be consulted by all glaciologists.

the mechanism of motion is the same, there is a great difference between the two cases, owing to the thrust exerted in the second case along the line of slope. This thrust is a result of the solid character of the ice (that is, the framework of immobile molecules), and is due to the weight of the glacier higher up the slope.

In a long straight glacier of uniform slope, temperature, thickness and cross-section, the thrust would be the same at all points along any line of flow, since the conditions would be exactly the same at all points along this line. This ideal condition is never realised; wherever an obstruction to motion arises, there will the thrust of the glacier above act with increased pressure on the section at the point of obstruction. If the obstruction is caused by a narrowing of the bed of the glacier, the ice molecules tend to move away from the point of increased pressure, and the depth of the glacier is increased by rise of the upper surface.

If the thrust from behind is too great, so that the forward movement of the glacier cannot proceed in the usual way, *i.e.*, by molecular movements within the ice, the upper layers of the ice may possibly shear bodily over the layers below, or over the obstruction in the bed of the glacier. The effect on a glacier when it meets an obstruction will, therefore, depend largely on the form of the obstruction; in every case, however, increased pressure will be developed, with a *tendency* to shear, either along the glacier bed or between layers of ice in the glacier; in every case, there will be a tendency to decrease the gradient of the upper surface of the glacier.

In the case of a narrowing of the glacier, this tendency will express itself in the formation of longitudinal pressure ridges; in the case of an obstruction in the form of a transverse ridge from bank to bank of the glacier, the tendency will express itself in the form of pressure ridges running parallel to and above the obstruction. A local obstruction such as a hillock on the bed of the glacier will cause local pressure ridges on the surface, whose form will be largely conditioned by the magnitude and form of the obstruction.

These pressure ridges are the outward and visible sign of a movement of the molecules away from the points of maximum strain.

The simple theory of glacier motion outlined above requires to be modified further to take account of the behaviour of ice under tension. As is well known, ice under tension and under pressure behave quite differently, only a comparatively small tension being necessary to rupture the ice, that is, to break the framework of rigid molecules. The limiting tensions necessary for fracture evidently occur very frequently in the normal glacier, both in high and in low latitudes.

If, for any reason, one portion of a glacier is forced to move faster than the neighbouring layers, and if this difference in speed is so great that it cannot be adjusted by molecular movements, either crevasses or shear cracks must divide the mass of ice nto two or more portions. If shear cracks form, they will lie parallel to the lines of flow of the glacier, while crevasses will be formed more or less at right angles to the main lines of flow. In a glacier flowing down a straight bed, transverse crevasses may form at every point where the slope of the bed is increased. In a bend of a glacier,

crevasses may form below the bend on the inner side of the glacier and in the lee of the projection, this part of the glacier being protected from the thrust of the portion of the glacier above, and therefore moving more slowly than the main stream of the glacier. Crevasses will also form at the junction of two glaciers moving in different directions and meeting at an angle, these circumstances being obviously particularly favourable to the formation both of crevasses and of pressure ridges.

Closely allied to crevasses and shear cracks in the origin of their formation, are certain of the bands of blue ice and silty ice which are so numerous in many Antarctic glaciers. Particularly in the Antarctic, many crevasses, cracks, or holes, which extend up to the surface of the glacier become the repository of fine sand blown from the surrounding land masses by the high blizzard winds, or deposited by the action of water flowing down the glacier surface. Owing to the fact that the upper layers of the glacier move faster than the layers below, a vertical transverse crevasse does not remain vertical for long, but is drawn out into a surface as in Fig. 90, Chapter VII,* which represents in section successive positions of a crevasse originally extending from the surface to the base of the glacier. If the glacier is of sufficient length, the plane of the crevasse may become almost horizontal. Thus any silt originally drifted into, or otherwise deposited in, the crevasse, will finally lie almost horizontal, and will, in fact, at all places sufficiently far removed from the place of origin, lie parallel to the glacier bed. The same reasoning applies equally to crevasses which are originally oriented otherwise than at right angles to the line of general movement of the glacier, these also tending to form silt-bearing planes lying approximately parallel to the glacier bed.

Silt bands formed by other means, as by deposit on the surface of a glacier which is increasing in thickness by additions of snow on the upper surface, will also tend to become more horizontal, so that the general tendency is towards the formation of silt layers conformable with the glacier bed.†

It is very probable that the erosive action of the ice upon the glacier bed also leads to the formation of silt bands, particularly in positions where the movement of the glacier is impeded. In such places, the form of the consequent silt bands may be of very complicated and folded aspect, especially if shear takes place within the glacier. As the glacier moves further forward, however, the folds must tend to lie conformably with the glacier bed.

As previously mentioned the great majority of the bands of blue ice lie parallel to the silt bands and are formed (in many cases) in somewhat the same manner, the blue ice being directly due to the presence of water (later frozen) in crevasses, both transverse and otherwise, in shear cracks, and in pits and depressions lying on the surface. As in the case of silt bands, the whole tendency of the glacier movement is to bring blue bands, whatever their origin, into conformity with the glacier bed, except in the case of vertical longitudinal shear cracks, which being parallel to the direction of the glacier's motion are not changed in form as the glacier advances.

* Page 255.

† The causes of origin of silt bands in glaciers are dealt with in detail in Chapter VII.

The question of moraines will, no doubt, be fully discussed in the Physiographical Report, together, with the question of the erosive power of glaciers. It is desirable, however, to touch on certain aspects of the phenomenon which follow naturally from the considerations which have already been brought forward.

It is pointed out elsewhere that the amount of moraine material, whether in lateral, medial, or terminal moraines of Antarctic glaciers, is very much less than that lying upon glacier surfaces in more temperate regions. In part, this is due to the fact that the moraine is actually less in amount. Moreover, the effect of radiation is to cause the isolated stones and boulders to sink into the ice, and this process is assisted by the increased precipitation in the form of drift snow when the boulders form projections above the glacier surface.

As in the case of glaciers in warmer regions, there seems little doubt that the increased thrust upon rocks projecting from the glacier bed will result in increased erosion at these points. Probably the amount of englacial material in the Antarctic is comparatively small, though the effect of this material upon the glacier bed may be far-reaching. It has already been stated that those places where slip of the glacier upon its bed is most likely to take place, are those places where the thrust of the ice behind, owing to an obstacle in the path of the glacier, rises to exceptional values.*

Consider the case of a boulder fixed in a depression of the glacier bed. It is quite possible, provided the pressures developed on the boulder do not exceed certain values and the glacier does not slip on its bed, for the ice molecules to travel round the boulder without moving it. If these pressures are exceeded, however, the boulder will be gripped firmly by the ice and will be used as a tool for grinding and scraping the glacier bed. The amount of erosion on the bed will be greater the greater the amount of rock material which can be held as a tool by the glacier, and the places where erosion of this type will be most effective will be precisely those places where the glacier is most likely to slip on its bed, *i.e.* where thrust exerts its greatest effect.

Our view is, therefore, that up to certain critical speeds there is comparatively little erosion of the glacier bed. Above such speeds, erosion becomes more and more significant, until the efficiency of glaciers as eroding agents becomes comparable with that of other geological forces. If we apply this principle to the Antarctic Continent—or rather to South Victoria Land—we are compelled to the conclusion that here the ice covering of the continent has today a predominantly conservative effect. Certainly, the swifter of the Victoria Land glaciers must cause considerable erosion of their beds, but the great majority are moving below the critical speed for the rocks over which they pass. Plate CVI, showing striations in a soft tuff issuing from the face of the Barne

* Chamberlin and Salisbury (' Geology,' vol. i) claims to have observed definite evidence of shear in a horizontal plane causing overhang in the terminal cliff face of Greenland glaciers. To this action he attributes much of the movement in the lower portion of Greenland glaciers. One would judge from the photographs that this shear is associated with the occurrence of silt-bearing planes. Similar cases of overlap on a glacier face, though on a smaller scale, have been seen by us in the Antarctic, but in every case the phenomenon was due to differential ablation and thaw, as between the clear and silt-bearing ice.

Glacier, which only moves forward some 30 feet in a year, shows, however, that true erosion of a soft rock surface can take place even under such circumstances, and by no means all Antarctic glaciers have this extremely small movement.

One point which is of great importance to the glaciology of Antarctic regions must be briefly mentioned here. Due to the thrust from the portions of the glacier behind, sufficient pressure can be developed to push the snout of a glacier uphill for some considerable height, the height to which it can be raised being conditioned by the magnitude of the thrust. This effect has, we believe, not been adequately considered in arriving at estimates of the thickness of glaciers in previous epochs. Thus, the statement, that erratics are found 800 feet above the present Ross Barrier level on Cape Crozier, has, in some quarters, been assumed as proof that the general level of the Barrier surface once stood 800 feet higher than at present, a deduction which is certainly incorrect, though in what degree we cannot judge.

In some degree allied to the problem of glacier motion, is that of the formation of the (roughly) hexagonal marking where loose rocks lie, either on a slope or in a horizontal plane. The polygons vary in size from 50 feet across to only a foot or two, and their cause is far from clear. Plate II shows these polygonal markings on the slopes of Mount Cloudmaker.

The essential features of the polygons are :—

(i) The sides of the polygons are outlined by angular rocks of greater size than those at their centres, *i.e.* the largest rocks gravitate to the sides.

(ii) On removing the loose rocks, the sides of the polygons are found to coincide with vertical cracks in a cement of sand and ice, which become narrower as the depth increases, but may be 2 inches in width at the top.

(iii) The corners of the polygons are the junction of three such cracks.

As mentioned above, it is difficult to find a complete and adequate explanation for this phenomenon. The formation of the cracks can be referred to contraction of the ice-sand cement underlying the top dressing of loose rock, and the movement of the larger rocks towards the depressions which outline the polygons will be assisted by temperature changes, and the alteration in the seating of the larger rocks (supported at a few points only) caused by ablation of the ice portion of the cement. It is certainly of interest to note that the polygons are best developed in the *angular* morainic material which outlines a former glacier-covered bed. They are most strikingly shown after a slight snowfall accompanied by wind, which drifts the greater part of the loose snow into the main depressions, at the bottom of which are the small cracks which outline the sides of the polygons.

Rate of Movement of Antarctic Glaciers.

Few measurements have been made of the rate of advance of Antarctic glaciers, but clearly the movement of individual glaciers varies enormously.

Thus, Ferrar states that Blue Glacier moves forward less than 4 feet per year, and that the movement of the south arm of the Ferrar Glacier is less than 6 feet per month. The advance of the Ferrar Glacier opposite Cathedral Rocks between February 11 and September 20, 1911, has been observed by us and found to be only 32 feet from February to October in its most swiftly moving part, while Debenham estimates that the rate of advance of the Wilson Piedmont-Ice opposite Dunlop Island is from 10 to 20 inches in a day during the summer. The movement of the Barne Glacier on Ross Island we have found, on the contrary, to be only 30 feet in a whole year.

Drygalski states that the movement of the Continental-Ice at Gaussberg varies from 0·33 to 0·44 metres per day, while the " West-Eis " is stated to be stagnant.

Measurements by Taylor and Debenham of the movement of the Mackay Ice Tongue in January and February, 1912, show that its rate of advance in summer is about 2·8 feet per day, while we estimate the forward movement of Glacier Tongue to be of the same order of magnitude—probably about 2 feet per day.

The most accurate measurement of glacier movement in the Antarctic is, however, that by Shackleton's Party of the mean movement of the Ross Barrier during $6\frac{1}{2}$ years, *viz.*, 492 yards per annum.

It will be observed that the rate of advance of these ice formations is small for the glaciers which do not project a floating extension into the sea. Clearly, therefore this is evidence of our contention that all glaciers which have a reasonable rate of movement will advance until they reach the sea, and that the length of an Ice Tongue is related to the forward movement of the Land-Ice formation behind it.

These rates are smaller than those observed in similar ice formations, where such exist, outside the Antarctic. Thus, the Muir Glacier in Alaska has a maximum movement of about 7 feet per day, according to Reid *; the great Tasman Glacier in New Zealand, 46 cm. per day; the Karajak Glacier in Greenland, 18 metres per day. These are all large glaciers comparable in size with the Ferrar Glacier. The greatest valley glacier in the world, the Beardmore Glacier, has, in our opinion, a rate of movement not exceeding 3 feet a day, even in its swiftest moving portions. It is, however, unfortunate that opportunity could not be found to measure this movement. We feel that these low rates of movement in the Land-Ice formations of the Antarctic can probably be referred to the low summer and yearly air temperature of the Antarctic, though glaciers no doubt exist on this continent which will have movements comparable with those of the Greenland glaciers. If such glaciers exist, they will clearly, however, have sufficient movement to project a floating Ice-Tongue many miles into the open sea.

* " Alaskan Glaciers," ' Bull. Geol. Soc. Ann.,' vol. iv, pp. 32–41.

CHAPTER V.

CLASSIFICATION OF LAND-ICE FORMATIONS.

(1) Preliminary Discussion.

The formulation of a classification of Land-Ice forms, which shall be truly based on genetic considerations, is a difficult matter, and has been made more so by the circumstances attending the early study of lands which have been, or at present are, inundated to a greater or lesser extent with ice.

The more interesting features of the climate of Europe, throughout the period of the evolution of man and that immediately preceding his first appearance on the earth, are the occurrence of certain "glacial periods," which involved great extensions of ice both in Europe and America. Some portions of the dwindling remnants of the last of these great extensions in Europe have survived to the present day in the form of isolated ice sheets and glaciers, and it is these ice formations which have been the subject of the closest study for many years.

Until quite recent times, the conception of a glacier in the minds and thoughts of most European glaciologists was entirely formed from a knowledge of the "Alpine" type. As researches were carried further afield, it was natural that the attention of students of this science should be drawn next to the ice formations of the more southerly portion of the European polar lands. The glaciers of Norway were claimed by many to be of a type distinct from those of the Alps and the "Norwegian" type of glacier was defined and described.

Travel further afield again discovered yet other new types, first in Spitzbergen, then in Alaska, finally in Greenland. Each glacier or ice field was named after the region where it was first seen, and from which the description of the type example was brought back. Thus, from the first, glacial nomenclature was burdened with the terms "Alpine," "Norwegian," "Spitzbergen," "Alaskan," and "Greenland" glaciers. Even in the case of those men who recognised clearly that glaciers of all five types might occur in any one intensely glacierised* country, the force of tradition was sufficient to ensure the inclusion of the terms.

* The terms "glacierisation," "glaciation" and "snow line," as used in this memoir, are intended to convey the following ideas :—

"Glacierisation"—the inundation of land by ice (German, *Vereisung*).

"Glaciation"—the erosive action exercised by Land-Ice upon the land over which it flows.

"Snow line"—an imaginary line representing the contour below which permanent accumulation of snow cannot take place.

Controversies also arose over the definitions of the typical " Alpine," or the typical " Norwegian " glacier, etc. As knowledge of the processes of glaciation* increased, different interpretations were placed upon the observed facts, and rival schools of thought further confused the meaning of terms which had formerly had a less specialised application than was now applied to them. This aspect of the question is discussed at greater length in a later section of this chapter, where the classification put forward by the writers is compared with those previously formulated.

(2) The Glacial Cycle.

For the complete understanding of the genetic relationship between various ice-forms it is useful to summarise briefly the phases passed through by a land mass of large extent during a complete " glacial cycle." Let us take the case of a land, of sufficient size to afford a reasonable diversity of land form, and with a climate such that no permanent or semi-permanent snow and ice fields can exist upon it. We may then visualise the result upon such a land mass of a progressive decrease in temperature combined with relatively high precipitation.

Fig. 52.—The initial stage of the glacierisation of a land mass.

The first result of the lowering of temperature will be seen in an increase in the proportion of the precipitation which takes place at high altitudes in the form of snow. Snowdrifts will form in the higher depressions of the mountains, and gradually—as may be seen in almost any mountain chain of medium altitude in the temperate zones, and sometimes of high altitude in the tropics—the mountain tops above the snow line will become swathed in a mantle of snow and ice, whose thickness will depend upon the amount of precipitation and the size of the gathering grounds afforded by those portions of the mountain ranges which are above that line (Fig. 52).

As the temperature of the land mass and of the air above it continue to fall, the area permanently covered with snow and ice will increase in size, until the gathering grounds become sufficiently large to give rise to glaciers of considerable size.

The latter will then overflow the lower portions of the walls of the depressions which contain the parent firnfields, and will attempt to follow the courses of the already existing valleys of the stream-erosion landscape towards the lower levels of the land. At this stage in the glacial cycle, only the valleys of the highlands will be deeply covered with ice.

Higher up, the more gentle slopes and all depressions will be covered with a thin mantle of ice, but the steeper ridges of the mountains will stand forth against the ice

* *See* footnote on previous page.

as bare black ribs and peaks, and the higher portions of the uplands, between the ice-flooded valleys, will also be comparatively bare. It is at this period of the glacial epoch that " cwm " or " cirque " erosion will play a dominant part in the sculpturing of the ice-free portion of the highlands (Fig. 53).

If the glacierisation of the land progresses, however, the next step consists in a further accumulation of snow upon the firnfields of the mountain basins, a corresponding increase in the floods pouring down the valleys, and the shrouding in ice and snow of the more gently sloping uplands between the valleys which contain the main ice streams draining the highland *plateaux*. As this coating of the uplands becomes thicker, local icefields

Fig. 53.—The second stage in the glacierisation of a large land mass. The formation of " highland " ice and valley glaciers.

increase rapidly in number, the ice pours outwards along the lines of greatest slope from each icefield, concentrating in tributary valleys where such exist, but elsewhere spreading outwards more uniformly, and pouring over all depressions in the walls of the main valleys containing the ice streams from the highland fields. The mass of ice pouring off the land above the snow line towards sea level increases so fast that the thawing which takes place in the lowlands cannot keep pace with the supply. At this stage, the principal ice streams move forward so rapidly that they may debouch from their valleys on to the plains at the foot of the mountains, or even push forward into the sea itself. That invasion of the lowlands, which has given rise to the most interesting of the typically Antarctic Land-Ice forms, will then commence (Fig. 54).

Fig. 54.—The third stage in the glacierisation of a land mass. The ice streams debouch from their valleys and encroach on the plains at the foot of the mountains.

In the meantime, the glacierisation of the mountain regions continues so long as the supply of snow increases. The decreased temperature ensures that less and less of the snow which falls in these regions is converted into water during the warmer hours of the day, or the warmer season of the year. Thaw water plays a less and less important *rôle* in the sculpturing of the land, the ice continues to accumulate, and the minor irregularities of the land surface are smoothed over as the surface of the snow and névé fields steadily rises.

As the glacial cycle approaches its climax, the whole land surface, with the exception of sharp peaks and ridges, becomes swathed in a mantle of ice and snow,

beneath which, however, the larger features of the original contour are indicated by a series of undulations which become softer and softer as the white mantle increases in thickness, and tends to flatten itself, filling up the valleys and depressions at the expense of the accumulations upon the higher ground.

As the ice thickens, and more and more of the land becomes deeply covered, the "cwm" formation, which played such a predominant part in the sculpturing of the highlands in the early stages of the glacial cycle, becomes of less and less importance. The only glaciation which goes on beneath the more uniform sheet of ice is a general lowering of the land surface as the ice flows down wherever possible to lower levels, carrying with it the debris which has been produced by the frost-weathering, and by the "bergschrund" and stream erosion of the earlier stages of the cycle, and using this material to smooth off the projections and remove a portion of the general rock surface over which it moves.*

If conditions as regards precipitation and temperature are favourable for an advanced stage of glacierisation to be attained, we now see the gradual swamping of such isolated peaks and ridges as remain above the general ice level, while the ice streams in the lowlands increase in size and thickness, and make more and more headway against the denuding influences which still operate at or near sea level. Great sheets of ice swamp the lowlands; great tongues of ice now protrude into the sea. If the ice increases in amount and the mean air temperature continues to fall, the formation of sea ice in the winter, and a belt of pack-ice in the summer, much restrict the influence of the sea—that most powerful of all denuding forces—and at the same time afford a basis for the lodgment of yet further deposits and drifts of snow. The spaces between the Ice-Tongues may become filled with permanent sea ice, on which collect drifts which gradually accumulate to complete the fringe of land ice which forms a selvage, adding in no mean degree to the superficial area of continent or island.

As snow is piled on snow and ice on ice, both inland and along the shore, the ice sheet, which has now reached truly "continental" dimensions, becomes of smoother contour, until finally a gently rounded dome with a vast selvage of horizontal ice, free-floating in an ice-strewn sea, attests the local conquest of cold and snow over all the other agents of nature.

An extreme case can even be imagined where not a peak remains exposed, where the only evidence of the existence of land beneath the ice-mantle is afforded by the general shape of the dome and the height to which the ice is piled above sea level. Such a state of affairs must have been fairly closely approached quite recently in the history of the Antarctic Continent. Evidence abounds to show that, within comparatively recent times, the ice surface in many of the valleys at present occupied by glaciers stood at least two or three thousand feet above its present level, while islands far out to sea have been over-ridden by portions of the lowland ice sheet which must have spread

* By far the greatest erosion will take place in the original valleys where the ice is thickest. The tendency will be to emphasise the contrast between these main drainage lines and the less dissected areas between them, and also incidentally to straighten out the valleys.

outwards in all directions over the continental shelf (Fig. 55). In the world's history, however, a state of equilibrium appears usually to have been reached long before this stage. The Pleistocene ice sheets of Europe and America, although they reached continental dimensions, were never of sufficient size to swamp the land entirely. Even the greatest Antarctic extension for which there is definite evidence probably left many peaks and ridges still free above the ice surface.

To obtain the perfect examples of glacierisation at its maximum stage, it is necessary to narrow one's field of view, and to give closer attention to much smaller isolated land masses, examples of which are afforded by the smaller islands off a glacierised coast. From amongst these may be selected many which exhibit a miniature of the completely swamped continental land mass with its gently-sloping ice cupola or dome, and with flattened edges caused by the projection of its ice covering into the sea. Once this form has been assumed, further accumulation can only result in increasing the height of the dome, decreasing its slope, and increasing the size of the skirting pushed forth into the surrounding sea. Except where the latter abuts against similar sheets produced over other islands, or against steep rocks and islands which are not glacierised to any great extent, no great modification of form can be expected.

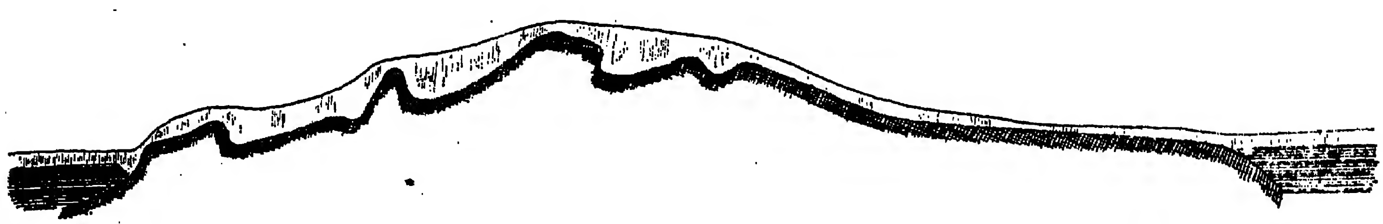


Fig. 55.—The ice inundation at its maximum flood. The whole land is swamped beneath a thick sheet of Continental-Ice which only betrays the presence of the more pronounced peaks beneath it. The lowlands are completely covered, and a selvage of floating ice extends far out to sea.

After the ideal dome-shaped form has been attained, and the ice sheet has grown to what is at once its simplest and most mature form, no great change can become evident, unless ameliorating climatic conditions cause a recession of the ice.

Comparatively small see-saw movements may take place as at any stage of the cycle, but if the deglacierisation of the land is progressive, a similar series of stages in the opposite sequence will take place after the glacial cycle has passed its maximum. It is to this portion of the glacial cycle that one must attribute the majority of the ice forms which have been described in detail.

The earliest stage during the process of deglacierisation, where a portion of the land is still swamped to such an extent that even its major irregularities are hidden, is represented by the great ice sheets of continental size which occur in the Antarctic and in Greenland. The stage where the ice covering remains on all gentle slopes, but is in the main moulded to betray all but the lesser irregularities of the land surface, can be recognised in portions of both the above countries and in Norway, Spitzbergen and Alaska. The stage where the icefields from the uplands have largely disappeared, and the glaciers in the valleys have shrunk to a shadow of their former size, can be especially well seen in portions of either of the latter countries. Finally, the firnfields

and glaciers of the Alps furnish a good example of the penultimate stage in the deglacierisation of a land mass. Here the majority of the glaciers do not even enter the valleys down which they formerly flowed, but head in secondary scallops of the great cwms which formerly held the snowfields which nourished their ancestors. Long before they have passed the lips of the cwms the area where alimentation is balanced by denudation has been reached. The drainage down the original U-shaped glacier valleys is all in the form of water, either the product of the wasting away of the glaciers and snow-drifts of the higher levels, or the direct result of precipitation in the form of rain on the slopes which border the valleys.

Finally, as the temperature ameliorates still further, the snow line shifts further and further up the slopes of the mountains. In all temperate regions of the earth, examples may be seen of the snow-capped peaks which are typical either of the earliest, or latest stages of the glacial cycle. Should a further general rise of temperature take place, the permanent snow-drifts may disappear altogether, as is the case with many mountains which shared in the Pleistocene glacierisation, but which are now snow free. Examples could be multiplied indefinitely, but such amplification of the subject would serve little purpose.

The broad features of the ice formations of the typical glacial cycle have been indicated in the above description. At any stage near the maximum, we have the ice sheets which accumulate in the highlands, on the uplands, and in the local depressions of the latter; these drain down to the lowlands through glaciers flowing down the pre-existing valleys of the preglacial drainage system, or may, under the influence of favourable circumstances, such as the occurrence of planes of weakness as, for instance, faults or weak bands of rock, scoop out fresh valleys for themselves which are discordant with the former drainage system. The mountain peaks and ridges are being quickly eaten away on all their main faces by cwm erosion, and, in the more advanced stages of the epoch, the fragments from the interior and sides of the cwms are being rapidly removed by "spill-over" glaciers heading in the cwms and flowing over their front steps in the attempt to find their way into the main valley glaciers.

Finally, at lower levels, there are a number of ice forms which are of particular interest and which owe their existence to a variety of factors. Chief among them is that accumulation of ice which results from the overflow from the various highland and upland sheets, poured on to the plains or into the sea, either directly down the slopes of the foothills, or through the valleys which seam the latter.

During the period of less intense glacierisation, we find a variety of incomplete forms, all of which can, however, be clearly visualised as being either the ancestors or the remnants of the ice forms mentioned above. Such ancestors are the early firnfields and glaciers of the mountain regions, the comparatively thin "ice-caps" of the upland districts, and the "expanded feet" of the more vigorous glaciers which outpass their confining valley walls and debouch upon the plains, often to coalesce and form true

" Piedmont " ice. Such remnants of a former greater glacierisation are the firnfields and glaciers of regions like the Alps, heading in small secondary cirques within greater cwms, or occupying only a very small portion of their former valleys.

The point of chief interest which is emphasised by any general survey of a hypothetical glacial cycle, or of the existing examples of stages in such a cycle, is the genetic relationship between all Land-Ice forms. Detailed classifications may be attempted, as will appear, based on the relative importance of the different factors which promote the glacierisation of the land; on the degree of glacierisation attained; or upon the relief of the glacierised land: but all such divisions are of a somewhat artificial nature.

All the types created in any such classification will pass one into another by imperceptible gradations. There can be no such thing as a sharp line of differentiation between types. Nature in this, as in most other manifestations, progress uniformly and steadily, and the best classification of glaciers can only be one which picks out arbitrary types whose form, position, or other characteristics, enable them to be easily defined and easily recognised from definition.

(3) Previous Classifications.

Of previous classifications, we need only mention those which have embraced the Land-Ice forms of the Polar regions, where glacierisation at the present time is developed ;o its greatest extent. Polar Land-Ice was first studied comprehensively in the Arctic :egions, and, before the close of the twentieth century, European glaciologists had 'ecognised three principal types of glaciers, to which had been given the names " Alpine," ' Norwegian," and " Greenland," respectively.

In 1897, E. von Drygalski* adopted a slightly different classification, dividing the ce-forms of the latter country into :—

(1) " Inland-Ice and inland ice streams," and
(2) " Highland-Ice and coast glaciers."

His criterion in distinguishing between the two classes was their relationship to ıe land surface upon which they lay The former was recognised by him as an ice ıundation which swamped the land; the latter as an ice covering which adapted itself › the land. He says of his classification, that the difference is in the main quantitative, ıt it depends on the origin of the ice and expresses itself in its motion. In sub-dividing :s second type, he uses the terms " Alpine " and " Norwegian " glaciers.

While the glaciers of Switzerland, Norway, Spitzbergen and Greenland were providing an object for the exploration of European glaciologists, those of Alaska proved ı equally fruitful field for the investigations of glaciologists of the United States. ı 1893, in a paper describing the Malaspina Glacier, I. C. Russell† gives a classification : Land-Ice forms in which he divides them into " Alpine," " Piedmont," and " Connental " glaciers, with a subordinate type to which he gives the name " Tidewater " aciers.

* E. von Drygalski, 'Grönland Expedition,' vol. 1, 1897.

† I. C. Russell, " The Malaspina Glacier," 'Journ. Geol.,' vol. 1, 1893.

Gilbert,* in his report on the glaciers met with by the Harriman Alaska Expedition, adopts the same main types, but refers to all valley glaciers as "Alpine" glaciers, and divides these latter into "tidal" and "non-tidal," according as they do or do not reach the sea. Another sub-type which debouches from the mountains on to the plain at their feet is well described in the same memoir, under the title "expanded foot" glaciers.

Since the beginning of the twentieth century, the Antarctic regions where the glacierisation of a large land mass (and of smaller subsidiary island areas) is now developed to the greatest extent, has been partially explored by many expeditions of which a trained scientific staff has formed an important part. The Antarctic Continent and the islands off its coast contain all the known types of Land-Ice forms, and the larger examples are displayed on a most magnificent scale.

The scientific exploration of the Antarctic coast and interior has resulted in classifications of Land-Ice forms which have been formulated in turn by Arctowski,† Phillippi,‡ Werth,§ Drygalski,|| Ferrar,¶ Gourdon** and Nordenskjöld.†† Finally, in his comprehensive book, 'Characteristics of Existing Glaciers,' Hobbs has reviewed the results obtained up to the date of the first Shackleton Expedition (1907–9), and has himself suggested a classification based upon a study of the literature of both European and American glaciologists.

A comparison of the classifications of Gourdon, Werth, Ferrar, Nordenskjöld, and Hobbs is given in Table VII, where the types are arranged, so far as possible, so that type-names occurring in the same horizontal line refer to similar ice-forms. It is at once apparent that there is little real agreement between the different classifications, while, in some cases, the same name has been used for types widely different both in method of origin and in form. The individual drawbacks to these classifications, as they appear to the writers, are discussed at a later stage in this chapter. Each classification is, however, a considered endeavour to solve a difficult problem, and criticism would be of little service unless a further attempt at solution were made. Before, therefore, any detailed discussion of previous classifications is entered upon, it is proposed to outline an alternative classification in which an attempt has been made to overcome various disadvantages inherent in the earlier ones, to sweep away various obsolescent names which have come to possess widely different meanings; to eliminate place names (which by their very nature are liable to cause confusion of thought); and to simplify the problem, so far as possible, by defining types with reference to certain physical factors which are generally acknowledged to have a distinct bearing on the ice-forms

* S. K. Gilbert, 'Harriman Alaska Exp.,' "Glaciers," vol. 3.

† Arctowski, 'Die Antarktischen eisverhaltnisse,' etc.

‡ Phillippi, 'Zeit. für Gletscherkunde,' vol. 2, 1907.

§ Werth, 'Deutsch Sudpolar Exp.,' 1901–3, vol. 2.

|| Drygalski, 'Die Sudpolar Forschung und die Probleme des Eises.

¶ Ferrar, 'Scientific Reports of Disc. Exp.,' 1901–4, "Geology."

** Gourdon, *loc. cit.*

†† Nordenskjöld, Die Schwedische Sudpolar Exp. und ihre Geographische Tätigkeit.

Table VII.

Heim.	Werth.	Ferrar.	Gourdon.	Nordenskjöld.	Hobbs.	Wright and Priestley.
Greenland Type.	Greenland Type.	Inland-Ice. Local Ice Caps.	Inland-Ice.	Continental Glacier. Inland-Ice. (*a*) Antarctic Type. (*b*) Arctic Type. Ice Cap. Highland-Ice. Almost completely iced mountain regions.	Ice Cap Type. Nivation Type.	Type i. Ice Formations of the area of predominant supply. (*a*) Continental-Ice. (*b*) Island-Ice. (*c*) Highland-Ice. (*d*) Cwm-Ice. (*e*) Snowdrift-Ice.
Norwegian Type. Alpine Type.	Norwegian Type. Alpine Type.	Greenland Glaciers. Norwegian Glaciers. Alpine Glaciers. Hanging Glaciers. Ice-Slabs.	Glaciers proprement dit. (*a*) Encaissé Glaciers. (*b*) Glaciers plat. Hanging Glaciers.	Mountain Glaciers.	Transection Type. Dendritic Type. Inherited Basin Type. Tidewater Type. Horseshoe Type.	Type ii. Ice Formations of the area of predominant movement. (*a*) Wall-sided Glaciers. (*b*) Valley Glaciers.
	Alaskan Type.	Piedmont Glaciers.	Piedmont Glaciers. Ice-Foot.	True Piedmont Glaciers. Glaciers of the Coastal Zone and the Shelf. (*a*) Ice-Foot Glaciers. (*b*) Shelf-Ice.	Expanded Foot Type. Piedmont Type.	Type iii. Ice Formations of the area of predominant wastage. (*a*) Expanded Foot-Ice. (*b*) Ice-Tongues afloat. (*c*) Piedmont-Ice. (*d*) Confluent-Ice. (*e*) Avalanche-Ice.
						Type iv. Ice Formations of the Zone of Balanced Forces. (*a*) Shelf-Ice.

Comparative table of classifications of glaciers by authorities who have taken into consideration both Arctic and Antarctic types. With these, are compared one by Heim based on Arctic types alone and that advocated by the writers. So far as possible, similar types occur in or near the same horizontal line.

which come into existence at different stages in the glacial cycle, and which occupy different relative positions on a glacierised land mass.

(4) Factors on which a Natural Classification must be Based.

A study of ice forms at an advanced stage of the glacial cycle shows various factors which enter into the glacierisation of the land, or which may affect to some extent the shape and size of various portions of the ice mantle. Any natural classification must be based upon one or more of these factors, which are in the main interdependent and inseparable one from another.

The factors which are most directly associated with the degree of glacierisation of a land surface are those of—

(1) Temperature,
(2) Precipitation,
(3) Slope,
(4) Denudation.

Given favourable conditions, the normal ice sheet during an advanced stage in the glacial cycle will stretch in unbroken extent from the highlands or uplands, through valleys and over slopes, to the lowlands or even into the sea, and it is on this " normal " form that the broader divisions of a genetic classification must be based. The " normal " ice sheet itself may be divided into three more or less distinct zones which are diagrammatically shown in Fig. 56 :—

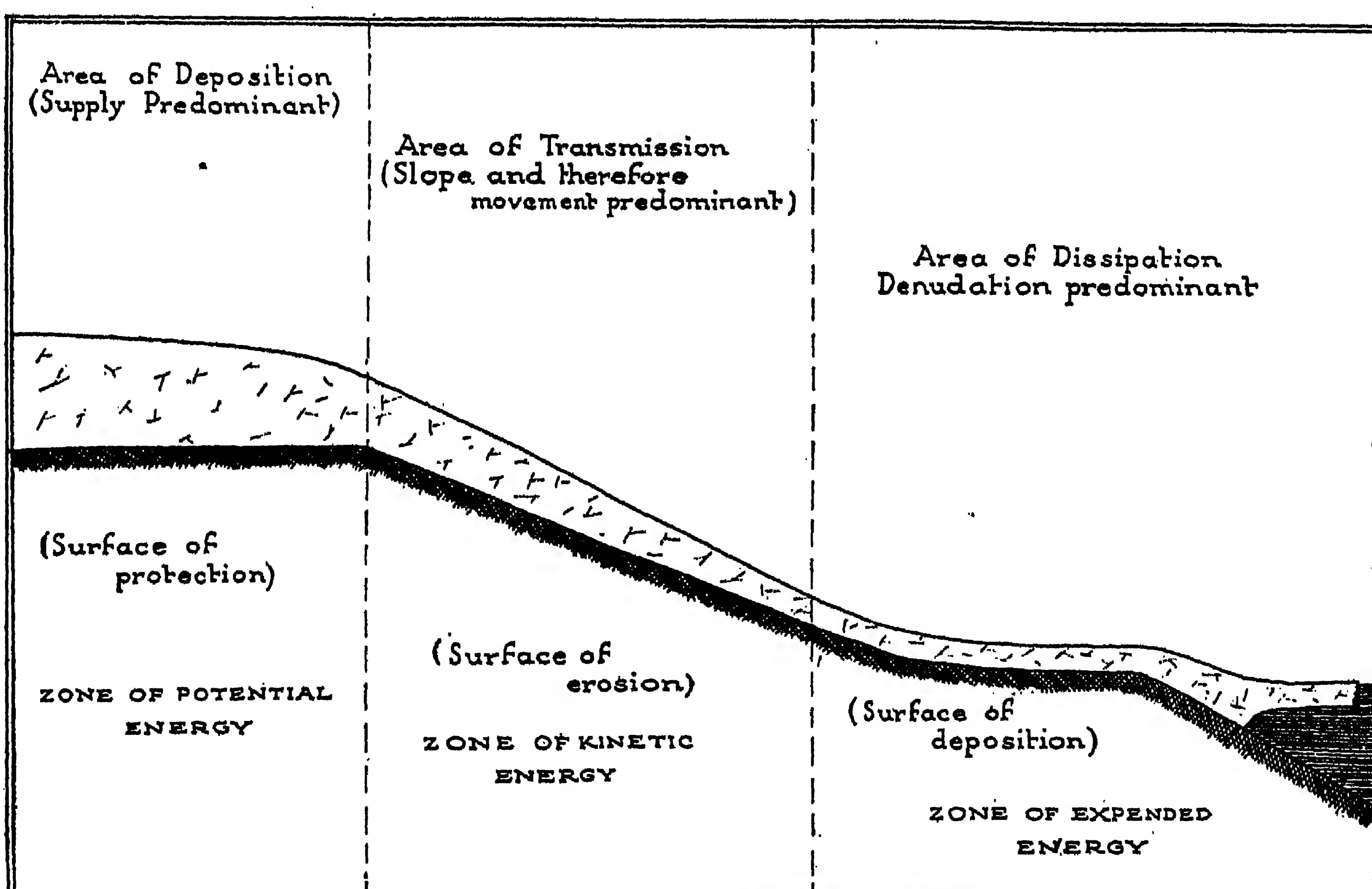


Fig. 56.—Chart showing the normal glacier form, with the three areas into which it has been divided for the purposes of this classification. The factors actually made use of are those above the diagram of the ice-form.

Temperature.

The effect of regional differences in temperature upon the ice-form will be seen in the presence or absence of one, two, or all three of the zones in a " normal " glacier, and temperature is therefore of first importance in causing different abnormal ice-forms, while it is, of course, the decisive factor which determines the relative importance of, and the position of, the zone of equilibrium separating two important factors—" supply " and " wastage." A suitable temperature is essential before a " normal " ice sheet can grow.

Precipitation.

The importance of " supply " in the form of direct precipitation of snow is, of course, unquestionable. It takes effect along the whole length and breadth of the ice sheet, but is predominant only above the position where its effects become somewhat neutralised by the rapid movement of the ice, or by the various forces tending to cause its disappearance.

The main effect of this factor upon the shape of the ice-covering over the land will be its ability or inability to swamp, and so to mask, the relief which gives their characteristic form to many of the Land-Ice sub-types of the earlier and later stages of the glacial cycle. This factor will also modify the results which might otherwise arise from the factor previously considered—temperature. An exceptionally high precipitation will cause the glaciers to push rapidly down to the lowlands and will result in heavy accumulation of ice along the coast and in the sea. The true " snow line " may then be lowered, irrespective of temperature, and a greater glacierisation may take place in spite of a relatively warm climate.*

Similarly, starvation may produce the opposite effect, and has, indeed, very probably played a large part in the denudation of ice which has characterised recent times on the Antarctic Continent. Here the average yearly temperature is possibly lower at the present time than at the time of the maximum accumulation of ice.

Slope.

The slope of the land is also of great importance in determining the types of ice-form. It is indeed to their considerable slope that the true " glaciers " owe their characteristic features. They are " rivers " of ice, pouring down from the regions of predominant supply to those of predominant wastage, where the ice becomes dissipated as icebergs, water, and water vapour.

Denudation. (*Wastage.*)

The fourth factor to be considered is that which sets the final limitation to the outward extent of the ice sheets. Throughout the whole area covered by the ice sheets, the denuding agents—sun and wind in the higher regions; sun, wind, rain and sea in the lower—wage continual war against the ice.

* For example, in Alaska.

Below the "snow line," these forces are predominant, and determine the limit and give the characteristic form to the ice-formations in the third zone. During the earlier and later stages of the glacial cycle, even the second zone—the zone of predominant movement—may be considerably reduced in extent or eliminated altogether. Supply and wastage become predominant in turn at the same level in a slightly glacierised country; they may each reign at the same spot at different times of the year, or even at different hours of the same day. As a limiting factor, therefore, denudation is bound to play an important part in deciding the exact extent and shape of the ice-forms produced at all stages of the cycle.

Two factors which remain to be considered are the "size" and "relief" of the land mass in process of glacierisation. These factors are not so intimately associated with the processes of the glacial cycle as the four previously discussed.

It is self-evident that the form of ice sheet produced will vary greatly, both with the size of the land which is being glacierised and with its relief.

If the chief divisions of a classification appear to be best based upon the main factors which decide the degree of glacierisation, the sub-types can scarcely be determined and defined on better grounds than those afforded by the effect upon these factors of the "size" and "relief" of the land upon which they rest. The latter have played a very prominent part in previous classifications, and most of the sub-types given in Table VII are based upon one or other of them. Indeed, the modern tendency, as represented by the classification of Hobbs, is to use the relation of the ice to the physiographical features of the land as the most important criterion of the type to which the ice-form should be allotted.

The writers cannot, however, agree with this method of classification, which gives an altogether disproportionate importance to the comparatively unimportant ice-formations characteristic of the initial and closing stages of the glacial cycle.

Classification Adopted.

The main subdivisions of the classification proposed depend upon the factors essentially concerned in the processes of the glacial cycle, viz., temperature, precipitation, slope and denudation. Certain subdivisions are, however, based upon the "size" and the "relief" of the land upon which the ice rests. Fig. 57, which again shows the three different zones of the ice sheet during any of the maximum stages of the glacial cycle, gives the main subdivisions grouped beneath the zone to which they naturally belong. Some forms which are the result of a peculiar balance between the conditions predominating in the three zones, and are also dependent upon their position at sea level, are grouped together in a fourth division.

It is considered that all Land-Ice sheets and streams must fit into the classification here outlined, though many cannot be referred directly to a single type. The ice covering of any land in an advanced state of glacierisation, if fully developed in all three zones, would be described as a sub-type of (i) in zone I, plus a sub-type of (ii) in zone II, plus a sub-type of (iii) in zone III.

Where less fully developed, any of the sub-types might be missing. Thus, the glaciers of the Alps will consist of a gathering ground (zone I) of either type i (*c*) or (*d*), which may or may not be prolonged by a glacier proper (zone II) of type ii (*b*). The "expanded foot glacier" of Gilbert may arise in a gathering ground of type i (*c*) or (*d*), continue through the zone of predominant movement as a glacier of type ii (*b*), and debouch upon the plain at the foot of its valley as an ice sheet of type iii (*a*). The normal ice-

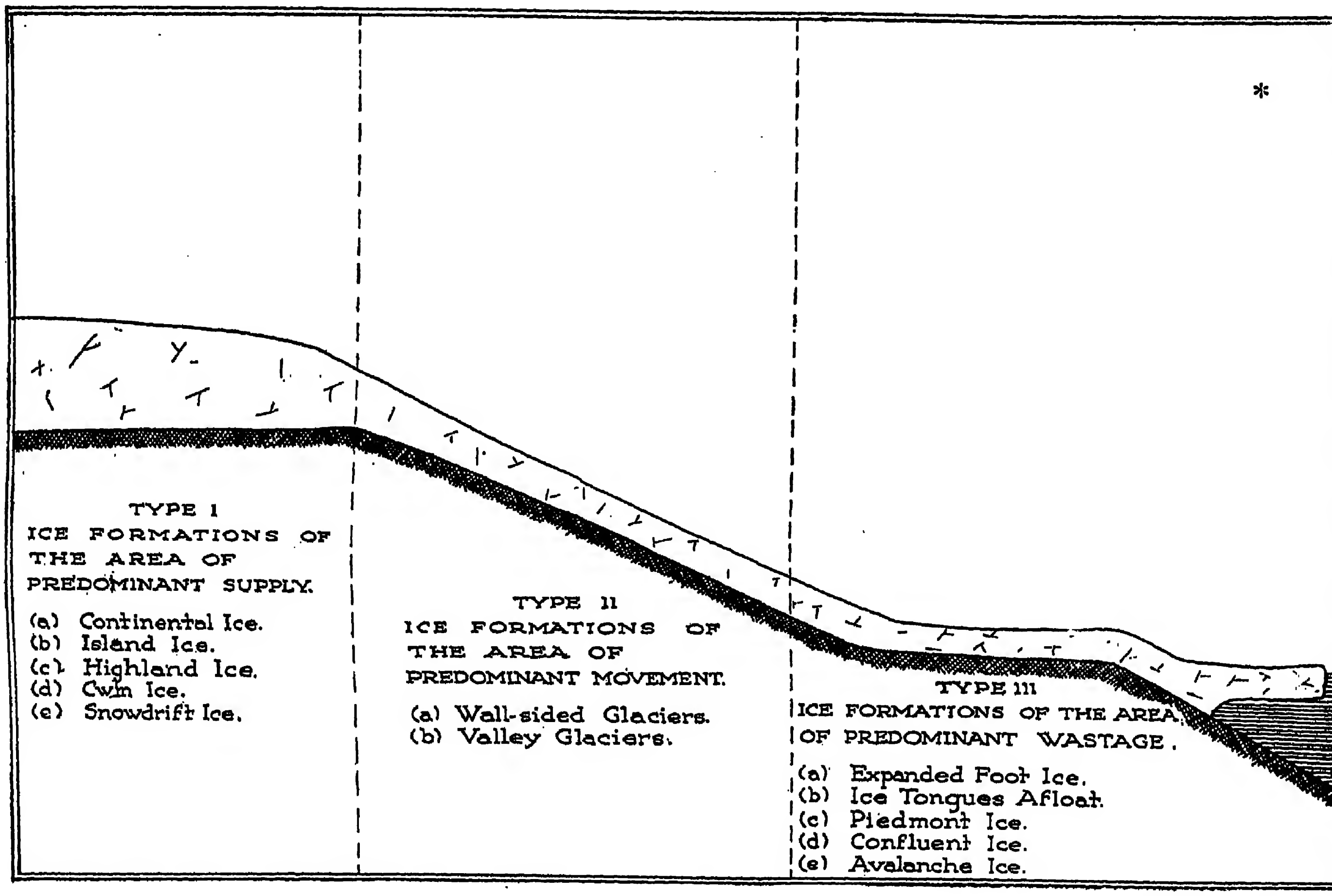


Fig. 57.

formation of the Antarctic Continent at its greatest development commences as an ice sheet of type i (*a*), passes the zone of predominant movement as a glacier of type ii (*a*) or (*b*), and pours into the sea, either as an Ice-Tongue of type iii (*b*), or as a portion of a sheet of type iii (*d*), or may be absorbed in a piedmont of type iii (*c*), or in a mass of ice (of varying origin) of type iv (*a*). The ice covering of any strongly glacierised island is of type i (*b*).†

* To these three types must be added :—Type IV. Ice Formations of the Zone of Balanced Forces; (*a*) Shelf-Ice.

† Occasional anomalies will occur in this as in other attempted classifications. Thus the "ice slab" of H. T. Ferrar is a glacier which is cut off from its gathering ground and lies inert in a portion of the valley formerly occupied by the ancestral normal ice-form of which it is a remnant. It occurs wholly within the zone described here as the "area of predominant movement," and yet is a typical example of an ice remnant in the characterisation of which the agents of denudation play by far the most conspicuous part.

(5) Definition and Examples of Individual Sub-Types.

Type I.—Ice Formations of the Area of Predominant Supply.

The various sub-types of this class—the ice-forms of the areas where supply is predominant over all other factors—represent the successive stages in the conflict between supply and land-form.

Progressively from (*a*) to (*b*) and from (*b*) to (*c*), the factor of land-form becomes of greater importance. Sub-types (*d*) and (*e*) depend for their existence upon land-form and are of small size, though of greater importance than many other types from a physiographical point of view. The method of evolution from sub-type (*e*) to sub-type (*d*) is still a matter of controversy, while the effect which the ice-forms of sub-type (*d*) have upon the land-forms in which they have their being is still not well understood.* The characteristics of the various sub-types are defined as follows :—

Sub-type I (a).—Continental-Ice.

Definition.—*A " Continental-Ice" sheet is the ultimate result of the profound glacierisation of a large land mass. The criteria of a Continental-Ice sheet are the size of the land mass upon which it rests, which must be very large, and the fact that all or the majority of the irregularities of the surface of the land are swamped by the accumulation of ice upon it, and are therefore not reproduced in modified form on the surface of the ice sheet.*

The margins of a sheet of Continental-Ice may show undulations due to land forms beneath it, but it is then passing into " Highland-Ice " of sub-type i (*c*).

(The equivalent of " Continental-Ice " in previous classifications will be found under " Inland-Ice " (Drygalski, Gourdon and Ferrar), " Greenland Glaciers " (Heim), " Continental Glaciers " (Nordenskjöld), " Ice-Cap Type " (Hobbs).

A hypothetical section through the Continental-Ice of the Antarctic Continent is shown in Fig. 58.

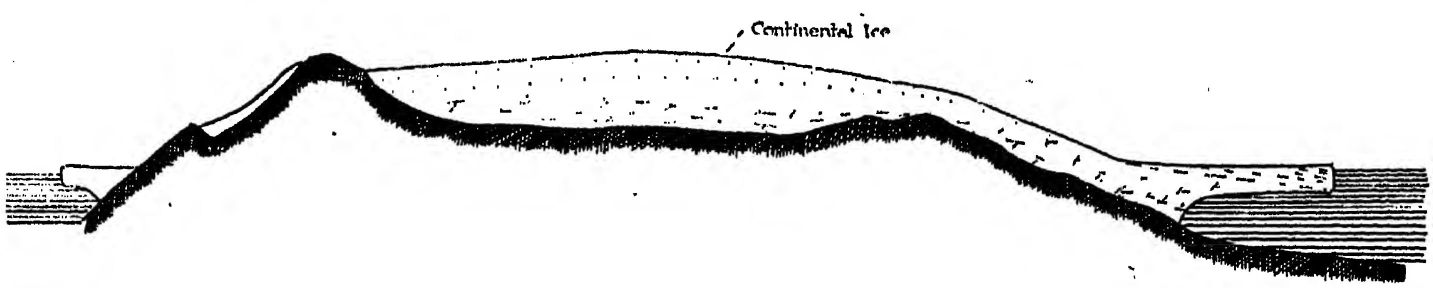


Fig. 58.—Continental-Ice. Most of the irregularities of the land are masked by an ice dome, the upper surface of which is gently sloping.

Sub-type I (b).—Island-Ice.

Definition.—*The ice sheet covering a small isolated, heavily glacierised land mass (Island).*

The minor irregularities of the land are swamped as in the case of Continental-Ice, but the small size and relatively steep slopes of the island cause the ice to assume a dome shape which is most characteristic.

* These questions, as applied to Antarctic conditions, are discussed in the Physiographical Memoirs of the Expedition.

The dome may be continued out to sea by a flattened selvage of ice, if precipitation is sufficient to cause great accumulation and rapid outward movement, which pushes the boundary where supply is balanced by denudation well beyond the island shore.

Through insufficient supply and increased temperature, Island-Ice will be transformed into a combination of Highland-Ice (sub-type I (*c*)) and glaciers of sub-type II (*a*) or (*b*), or, if the island is very small and somewhat steep, it may disappear altogether under the disruptive influence of the sea forces. (Its equivalent in previous classifications is the " Local Ice Cap " (Ferrar), and " Ice Cap " (Nordenskjöld), and it is included presumably in the glaciers of Greenland type of other authors.)

Fig. 59 shows Island-Ice with and without a floating selvage.

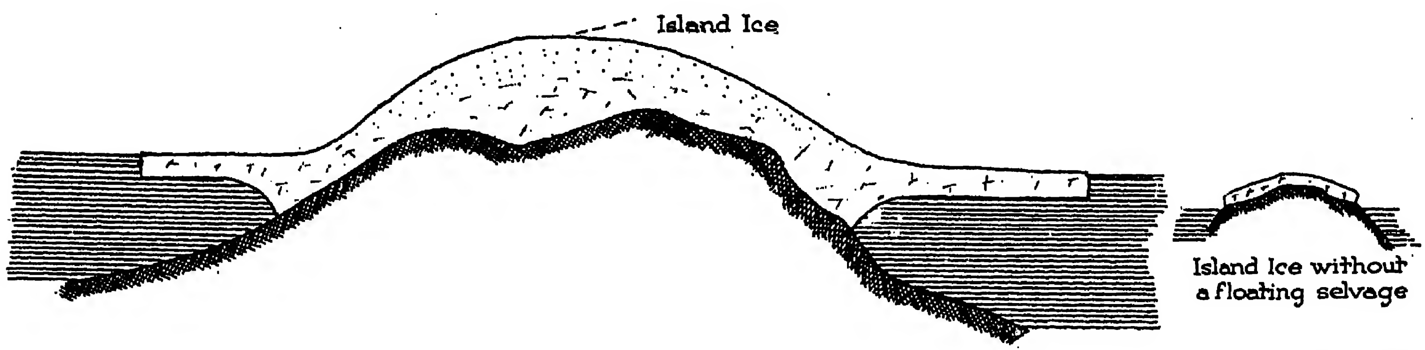


Fig. 59.—Island-Ice. A pronounced dome shape with or without a flattened selvage of floating ice. Characteristic of the complete inundation of a small isolated mass of land.

Sub-type I (c).—Highland-Ice.

DEFINITION.—*A comparatively thin, but continuous, ice sheet, overlying any flat or undulating land surface and conforming to a considerable extent to the irregularities of the land upon which it rests.*

Highland-Ice is the result of the glacierisation of the highlands and uplands of a land mass which is not completely swamped beneath a sheet of Continental-Ice or Island-Ice. The essential difference between this and the two sub-types previously defined is, that the shape of the upper surface of the ice conforms to all the major unevenness of the land-forms upon which it rests.*

By a process of starvation, Continental-Ice may be resolved into several sheets of Highland-Ice. This process seems to have taken place recently in Spitzbergen, where the former Continental sheet has been resolved comparatively recently into three separate sheets of Highland-Ice, separated by naked ridges of rock. In the Antarctic, numerous examples can be seen of sheets of Highland-Ice which have been left behind during the recession of the ice, and also of others which have probably never been other than local in extent.

* If an illustration from human experience may be cited, the essential difference between a sheet of Continental-Ice and one of Highland-Ice may be defined as equivalent to that between a " crinoline " and a " directoire " dress. The former conceals the contours of the form which it covers; the latter outlines the form in softer contours than may actually exist in nature.

Fig. 60 is a diagram of a sheet on the plateau-like surface of a cape in Robertson Bay. This sheet is also shown in Plate CVII. Plates CVIII and CIX are other typical examples of sheets of Highland-Ice which exist in South Victoria Land.

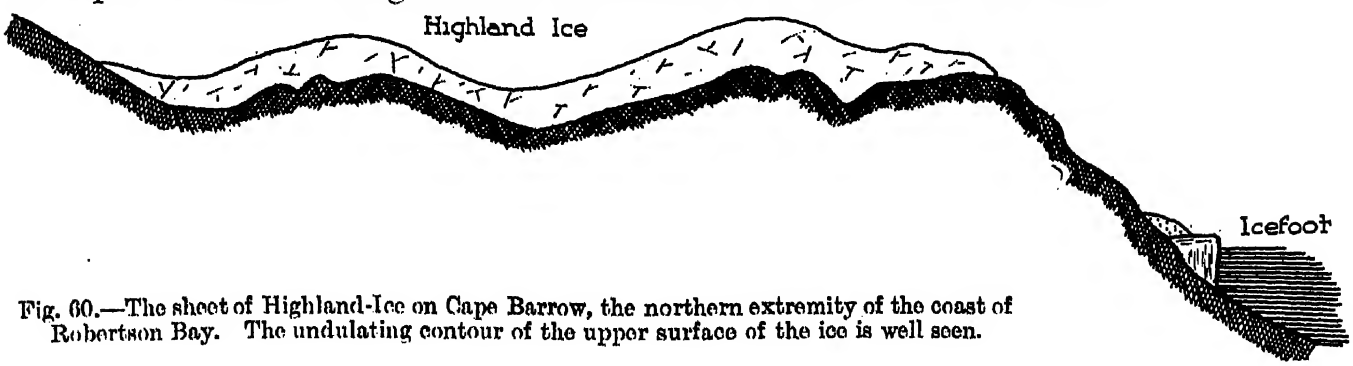


Fig. 60.—The sheet of Highland-Ice on Cape Barrow, the northern extremity of the coast of Robertson Bay. The undulating contour of the upper surface of the ice is well seen.

(Highland-Ice as defined above appears to be included by previous writers under the terms—" Norwegian Glaciers " (Heim and Werth), " Local Ice Caps " (Ferrar), " Inland-Ice " (Gourdon), " Ice Cap " (Nordenskjöld and Hobbs).)

Sub-type I (d).—Cwm-Ice.

DEFINITION.—*The ice mass occupying a cwm.* (Also called " corrie " and " cirque " by many writers.)

The " cwm," or " corrie," is a well-defined physiographical feature whose existence is admitted by all students of land-form who have personally visited countries partially inundated by ice, but the mode of formation of this land-form is still within the realm of controversy.*

The method of formation of the cwm will be discussed elsewhere ; for the present, its existence must be taken for granted. The ice mass which occupies the majority of the cwms of glacierised countries must be classed as a distinct sub-type in itself and it belongs naturally to the area of predominant supply.† (Plates CX and CXI.) Cwm-Ice is usually of so small a size, and is normally so embedded in steep rock slopes, that, where supply is not in excess of wastage, it would be very evanescent. That it may quickly disappear, even in countries where the snow line is close to or below sea level, is attested by the number of empty or half-empty cwms which may be seen in the more wind-swept regions of the Antarctic. Such empty or partially-filled cwms give a strikingly characteristic appearance to Antarctic scenery at high levels.‡

The maximum development of Cwm-Ice will be found at an early or late stage of the glacial cycle. As that cycle approaches a maximum, the Highland-Ice, and later the Continental-Ice sheets, encroach more and more upon the hitherto inviolate mountain sides, and the cwms with their quota of ice and snow are absorbed into the sheets of Highland-Ice, or swamped beneath the margins of the Continental-Ice. The larger ice

* For studies of the evolution of Antarctic Cwms from two points of view the reader is referred to the Physiographical Memoirs of the Expedition.

† The cwm glacier owes its existence to a very exact balance between the forces of supply and denudation. A slight change in either of these forces would cause its total disappearance, or its growth into a " spill-over " glacier headed in a cwm.

‡ There are also numbers of low-level cwms in the sides of the Beardmore Glacier and on the shores of the Ross Barrier in the neighbourhood of Mount Longstaff, which have the typical cwm shape at the back, and whose floor lies apparently a little below the upper ice level of the Beardmore and the Ross Barrier (Plate CXI).

sheets of the advanced stages of the glacial cycle play, however, a predominantly conservative and protective *rôle* upon the surface of the land. The cwms of the advancing ice age remain intact and, to a great extent, unmodified, beneath the Continental-Ice. The recession of the latter in the later stages of the glacial epoch once more uncovers them to form the parents of the greater cwms of the future.

In the final stages, the retreating ice will lay bare the sides and bottoms of the cwms themselves. Then, in the minor irregularities of their surface, snow and ice will remain or collect, and gradually fresh scalloped depressions of smaller area will be initiated within the parent cwm. As these increase in size, the ice masses within them may also grow, and a slight local increase of precipitation may cause the ice to spill over the rim and form what may be termed " spill-over " glaciers. Similar glaciers, heading in secondary scallops and extending out into the main cwm bottom, might also remain as remnants of the pre-existing cwm-ice of the earlier stages of the cycle. In either case the result would be the same, and the typical " Alpine " glacier of Hobbs appears to be nothing but a single specimen, or a collection, of such " secondary " cwm glaciers.

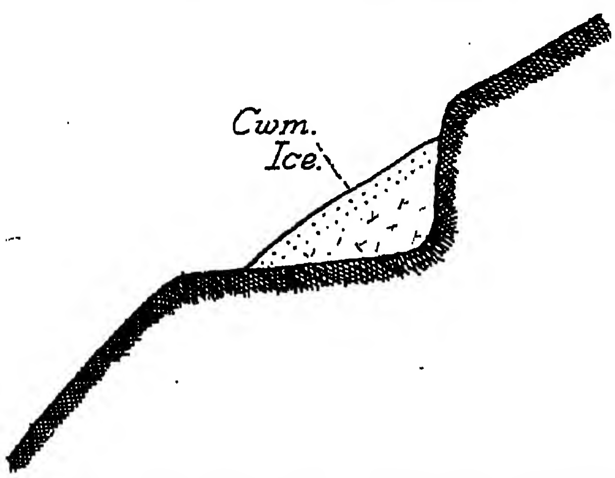


Fig. 61.—Cwm-ice occupying small cwm on hillside.

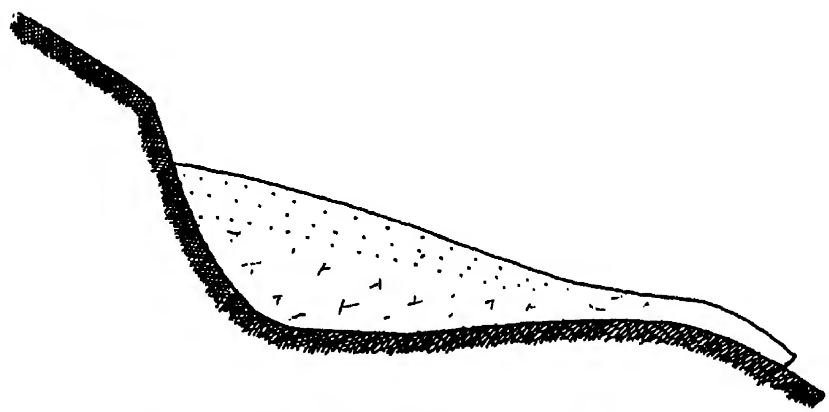


Fig. 62.—Cwm-ice with " spill-over " glacier draining it.

Cwm-Ice is usually developed on a much smaller scale than the sub-types previously described.

It is defined entirely by reference to the shape of the depression which it occupies or forms. The formation of the cwms has been ingeniously ascribed to " bergschrund " erosion, but in many cases—especially in the Antarctic, where bergschrunds are the exception rather than the rule—this explanation does not seem adequate to account for their prevalence and size. Cwms and masses of Cwm-Ice are extremely common features of the highlands of the Antarctic Continent, as they are, indeed, of all glacierised lands, and they give, perhaps more than any other single land or ice form, a characteristic appearance to those regions.

(Cwm-Ice has not until recently been differentiated as a separate sub-type. Cwm glaciers have, however, been defined by Hobbs, and most of those which spill over the edge of the cwm would be included in the definitions " Alpine " glaciers, " *Glaciers proprement dit*," and " hanging glaciers " of other authors.)

Fig. 61 is a section through Cwm-Ice, and Fig. 62 through Cwm-Ice with a " spill-over " glacier.

Sub-type I (e).—Snowdrift-Ice.

DEFINITION.—*Permanent and semi-permanent masses of ice or névé, which are formed by the accumulation of drifted snow in the lee of projections, or in depressions of the ground.*

Such a collection of drift snow can only persist long enough to merit the adjective "permanent" under fairly severe conditions, and Snowdrift-Ice is the initial ice-formation from which most Cwm-Ice seems to originate.

By increase of precipitation or decrease of temperature, or both, the masses of Snowdrift-Ice collected in the depressions of an upland region, or between the ribs of a mountain, may coalesce, and grow to form a sheet of Highland-Ice, and this in its turn may join with its neighbours and thicken to form a sheet of Continental-Ice. Thus, the relationship between all types of ice produced in the area of predominant supply is essentially dependent upon these factors.

Snowdrift-Ice may collect in the Antarctic at any altitude. At sea level, such consolidated drifts may play a prominent part in the formation of the Icefoot, and they have therefore been termed "Icefoot" by Gourdon and "Icefoot Glaciers," by Nordenskjöld. Though typically developed in the Icefoot region, however, their occurrence is so universal and their characteristics so independent of their position, that the writers consider a name associating them with a definite coastal ice-formation, which may itself owe its formation to any one of several processes, to be a mistake.

The method of origin is best indicated by the name now adopted. Snowdrift-Ice round the coast exercises a predominantly preservative influence on the land upon which it rests, as it protects the latter almost entirely from the inroads of the sea.

In other positions, however, masses of Snowdrift-Ice do assist to deepen the depressions in which they lie. The method by which this is done, and the method by which Snowdrift-Ice may entrench itself to form Cwm-Ice, cannot be discussed here.

This ice-form has not been dignified by a special name in the earlier glacier classifications, but it is of so widespread occurrence, and has such an interesting significance that no classification could be considered complete without its inclusion.

Amongst the examples in the Antarctic are numbered nearly all of the smallest Antarctic ice-forms, but on occasion Snowdrift-Ice may assume considerable dimensions along the coast without passing into another sub-type. These ice masses have a considerable significance as transporters of rock *débris*.

Their position in the present classification is difficult to decide, but, if they are to persist sufficiently long to make them worthy of inclusion at all, supply must at least equal wastage.* Since the factors limiting their size are usually the shape of the

* It is a significant fact that, at or near sea level, Snowdrift-Ice masses never appear to deepen the depressions in which they lie sufficiently to enable the latter to pass over into cwms. This is difficult to understand if cwms are due solely to "bergschrund" erosion. "Bergschrunds" are not common at any level in the Antarctic, and they certainly do not occur in the masses of Snowdrift-Ice, which are met so frequently at low levels. It would appear that some other action besides "bergschrund" erosion is essential to convert snow-drift depressions into cwms. Cwms occur in the Antarctic at sea level, but may not have originated there. Their position is probably due to a general subsidence of the coastline.

depression which they occupy and the size of the projections in the lee of which they lie, in practice supply usually exceeds wastage. A considerable quantity of the available drift is unable to find a lodgment, and is swept away " down wind." If supply does not exceed wastage, the snow-drift will quickly dwindle, and will be entirely removed in a very short time. Similar, but temporary drifts are, indeed, common in South Victoria Land, and may form and be removed several times a year. So quick is the change of snow into ice, however, that even these seasonal drifts may sometimes have the lower layers of the snow converted into ice. When examined, they cannot then be distinguished from their more permanent relatives; but this does not matter, since they fall very well within the definition of the same sub-type of ice-form.

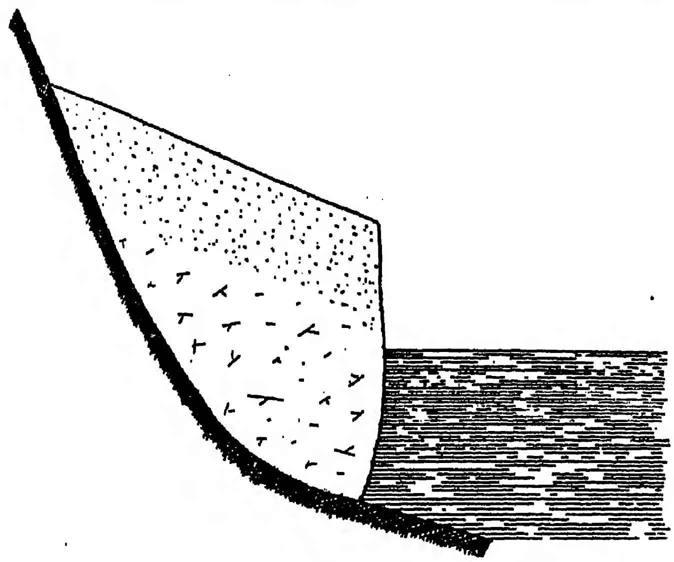


Fig. 63.—Snowdrift-Ice formed as a portion of an icefoot along a steep coast. This belongs to the " icefoot glacier " type of Nordenskjöld and Gourdon.

Diagrams of Snowdrift-Ice formed in the lee of a cliff and in a more gentle depression are shown in Figs. 63 and 64, Plate CXII is a photograph of a typical accumulation of Snowdrift-Ice which has become incorporated in the Icefoot, and Plate CXIII is a photograph of Snowdrift-Ice formed in a partial lee on Inexpressible Island.

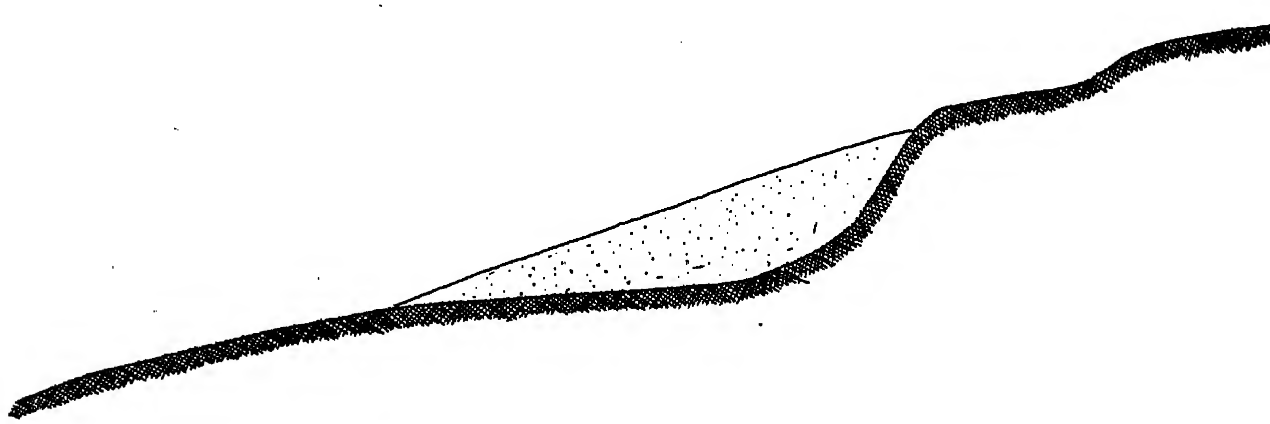


Fig. 64.—Snowdrift-Ice formed in a shallow depression.

Type II.—Ice Formations of the Area of Predominant Movement.

This class includes practically all the distributaries from the various ice-forms ncluded in type I. The characteristics of the glaciers of type II—for the ice-forms included in this division are true glaciers—are their relatively steep slope, their frequently rapid movement, and the fact that they are the connecting-link between the ice-sheets of the upper regions of the land mass and those of the foothills and plains.

Two sub-types are recognised according as the diffluents are, or are not, confined by valley walls.

Sub-type (II) a.—Wall-Sided Glaciers.

DEFINITION.—*Streams of ice originating in, and fed by, upland ice (ice of type I) of any description, and flowing down towards sea level unconfined by any marked valley wall.*

The ice sides of wall-sided glaciers overtop the ground to right and left of them. Should they occupy a depression, it is one unconnected with their own erosive action as a rule, and, in any case, the depression is relatively slight. The wall-sided glacier is often a comparatively recent remnant left by the irregular breaking back of a sheet of Highland-Ice or the thin margin of the Continental-Ice, or it may be a recent local extension of either of the above ice-forms due to a recent local increase of precipitation. The two sub-types may usually be distinguished by their form at their junction with the parent mass, and they are shown diagrammatically in Figs. 65 and 66. Wall-sided

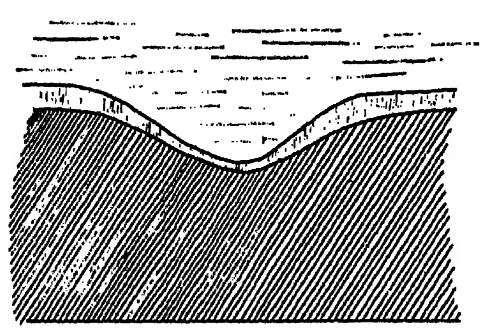


Fig. 65.—Wall-sided distributary, due to local advance in Highland-Ice.

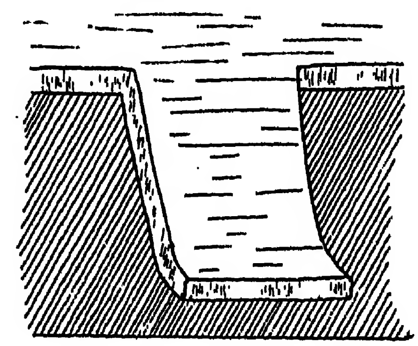


Fig. 66.—Wall-sided distributary, due to retreat of Highland-Ice.

diffluents from a sheet of Highland-Ice are shown in Fig. 67 and Plate CXIV. A lobate form with wall sides may be displayed by a glacier which is an overflow from a local firnfield, or a cwm, as in Plate CXV, which shows a small glacier near Warning Glacier in Robertson Bay. Plate CXVI shows one from the Ferrar Glacier region.

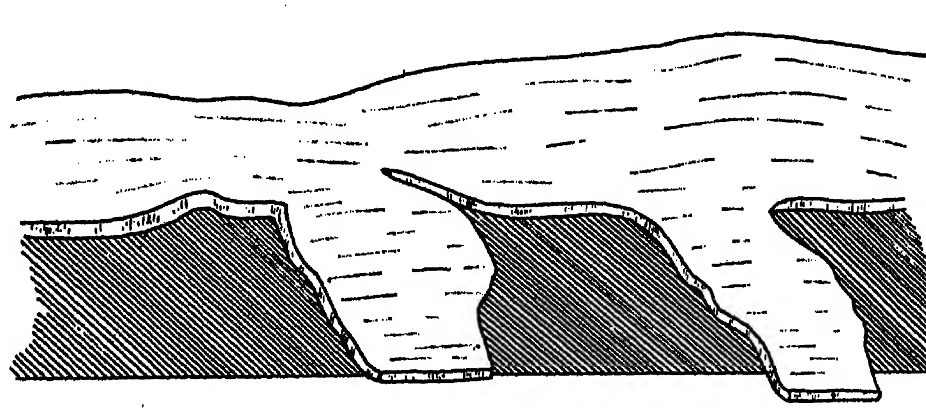


Fig. 67.—Wall-sided distributaries from Highland-Ice at Cape Barrow, Robertson Bay.

Glaciers of this sub-type are not nearly so common as valley glaciers, since the tendency is naturally for the main ice drainage to follow the valleys of the water-drainage system, which will have been deeply eroded during the period of heavy precipitation and torrential streams which is likely immediately to precede the inception of a glacial cycle. An additional reason for the preponderance of valley glaciers is the fact that, while ice sheets of type I exercise a predominantly conservative effect upon the land surface beneath them, ice streams of type II, where movement is important, will tend to lower their bed, except where they occur in such positions that sub-aerial

weathering is able to keep pace with their activities. Such a condition may be found in the case of glaciers flowing down the side of a relatively steep cliff face, as at Cape Barrow. The ultimate end of the glaciers in question is, however, likely to be brought about at no very distant date by the undermining action of the sea upon the rocks on which they lie, an action which is slowly taking place in spite of the protective influence exercised by the Icefoot.

(This sub-type is not recognised in previous classifications, unless by Gourdon in his sub-division—" *Glaciers proprement dit* ((*b*) *Glaciers plat*)"—It will, of course, fall within the category " mountain glaciers " of Nordenskjöld.)

Sub-type II (b).—Valley Glaciers.

DEFINITION.—*Streams of ice originating from and fed by upland ice (Ice of type I) of any description, and flowing down definite valleys towards sea-level.*

To the above type must be assigned all " entrenched " distributaries of Continental-Ice, Highland-Ice and Cwm-Ice. By far the greater number of true glaciers belong to

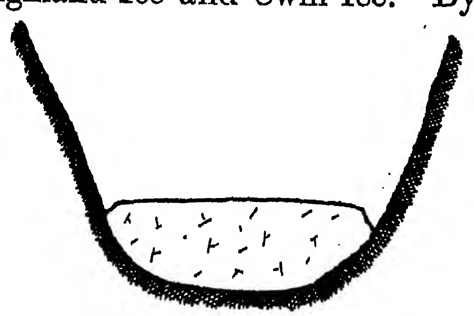


Fig. 68.—Transverse section through valley glacier.

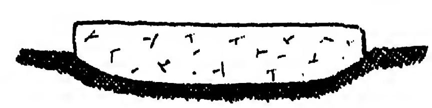


Fig. 69.—Transverse section through wall-sided glacier.

this type, which is represented in previous classifications by the " Alpine " type of Heim, Werth and Ferrar; the " hanging glacier " of Ferrar and Gourdon; the " *Glaciers proprement dit—(a) Encaissés glaciers* " of Gourdon; and the " mountain glaciers " of Nordenskjöld.

The essential characteristic of the valley glacier as opposed to the wall-sided glacier is, as the name suggests, the valley in which the glacier lies (Figs. 68 and 69). This valley may have been wholly or partially excavated by the ice itself, or may be merely " inherited " by the ice, and have remained substantially unmodified. This will depend in the main upon the age of the glacier, but it is quite irrelevant from the point of view of the present classification.

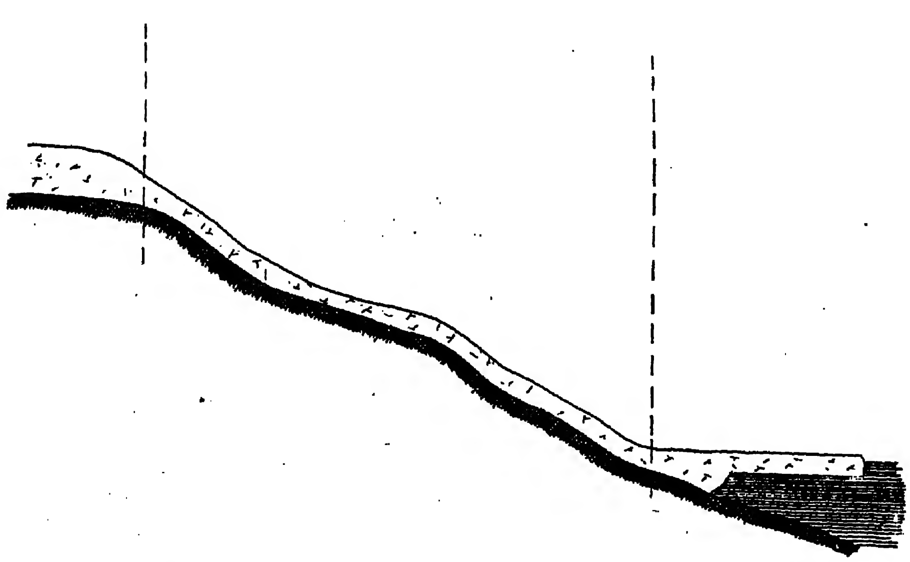


Fig. 70.—Longitudinal section through a valley glacier.

A longitudinal section through a typical valley glacier is shown in Fig. 70,

the valley glacier being that portion of the ice-formation which lies between the vertical dotted lines. Plates CXVII and CXVIII show, respectively :—

(1) A valley glacier draining Continental-Ice.

(2) A valley glacier draining Highland-Ice.

The above glaciers should be included within the confines of the sub-type at present under consideration.

Valley glaciers are characteristic of all but the initial and closing stages of the glacial cycle, though, when extreme glacierisation occurs, they will be hidden beneath the upper layers of the Continental-Ice, and will thus not appear as a recognisable type. It is through the medium of these entrenched ice streams that the most effective glacial erosion takes place.

Type III.—Ice Formations of the Area of Predominant Wastage.

The ice-forms grouped together under type III, as being characteristic of the area where denudation is predominant, all owe their existence to the debouching of the distributaries of type II, or of the unbroken edge of Continental-Ice or Highland-Ice upon the plains, or into the sea, at the conclusion of their descent from the highland or upland gathering grounds.

They are arranged from (*a*) to (*d*) in order of increasing size and importance. While the main mass of the ice composing them is derived directly from the glaciers; direct precipitation and snow-drift—even, on occasions, sea ice formed between individual "tongues"—may exercise a considerable influence in augmenting and compacting the more complex types.

In the main, however, the action most effective, and that which definitely limits the size of the individual ice sheets, is denudation by thaw, evaporation, ablation, and the melting and disruptive forces of sea and tide.

It is these forces which give their characteristic appearance and shape to the ice-forms, and it is to these forces that their disappearance is finally due when supply from above, transmitted through the medium of the valley and wall-sided glaciers, becomes insufficient or fails altogether.

Sub-type III (a).—Expanded-Foot-Ice.

Definition.—*The lobe of ice formed beyond the mouth of a valley glacier from which the ice debouches upon an unconfined plain.*

The type of the "expanded foot" occurs in Alaska, and this is a form which is uncommon in the South Victoria Land region of the Antarctic.* Such an ice-form might rather be expected to be characteristic of a land where glacierisation is due to excessive precipitation in a country where the snow-line is above the base of the mountains. In such a situation, examples might be expected of ice pouring down valley glaciers, in such volume and with such a speed that it would be able to make headway against

* It is only in such anomalous regions as the Dry Valley of the Taylor Glacier that this ice-formation is likely to occur in Antarctica (Plate CXXV).

denuding forces which would otherwise have been sufficient to remove the greater portion of the more stagnant ice at lower levels.

At a certain stage of the glacial epoch in such a land, numerous disconnected lobes at the end of such valley glaciers might be found if the foothills were bordered by a sufficiently broad coastal plain. In the Antarctic, conditions are more favourable to the development of Piedmont-Ice, Confluent-Ice, and floating Ice-Tongues.

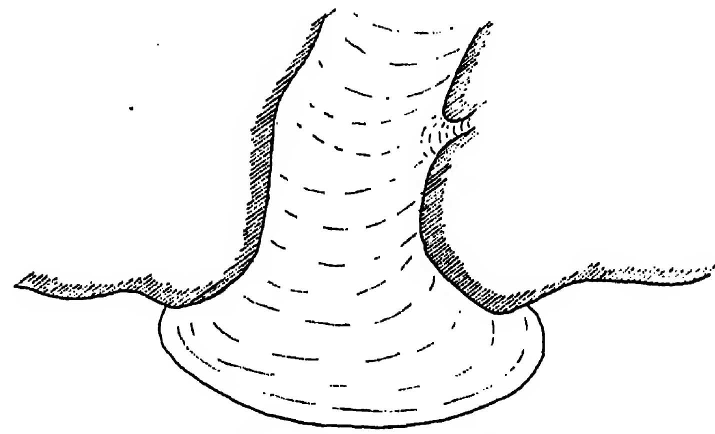


Fig. 71.—Diagram of Expanded-Foot-Ice.

(This type of ice has not been included in previous Antarctic classifications. It appears, however, to be a sufficiently distinct ice-form to merit notice and it is genetically related to the more common forms which follow (Fig. 71).)

Sub-type III (b).—Ice-Tongues Afloat.

Definition.—*Extensions of the ice of glaciers of Type II which persist so far out to sea that their ends are afloat.*

The Ice-Tongue afloat is perhaps the most striking of all the Antarctic land-ice forms. Indeed, this has been so much the case that Ice-Tongues have been mapped by expeditions, the personnel of which have never even descried or named the glaciers to which the Ice-Tongues owed their existence. Subsequent discovery and exploration of these latter has commonly led to the allotment of a different name to the glacier, and thus Antarctic glacial nomenclature has become unduly complicated. Examples are the Drygalski Ice-Tongue, which has its origin in the David Glacier, and the Nordenskjöld Ice-Tongue, which is fed by the Mawson Glacier.

The characteristics of the Ice-Tongue are, first and foremost, the long sub-triangular shape; secondly, a contour very gently convex from side to side and shelving gradually from the shore towards the sea end until the free floating portion is reached, when the upper surface becomes a horizontal plane. Crevasses are usually few at the seaward end, and the Ice-Tongue will be bordered all round its seaward face by sharply-defined perpendicular cliffs which lie between the limits of 10 and 200 feet in height.

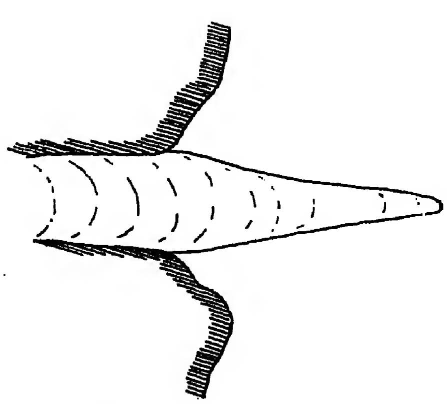


Fig. 72.—Plan of a floating Ice-Tongue.

The seaward end of a well-developed tongue rises and falls freely with the tide, and a tide-crack between it and the sea ice is therefore usually ill-defined or absent altogether. Forward movement may be rapid or slow, according to the degree of nourishment afforded to the tongue by the glaciers or ice sheet behind it.

A plan and section of an Ice-Tongue are given in Figs. 72 and 73, and of an actual case of a triple Ice-Tongue fed by two glaciers in Fig. 74. Photographs of portions of

Ice-Tongues are shown in Plates CXIX and CXX. The Shackleton Ice-Tongue on the coast of Queen Mary Land is the greatest example known, and extends out into the sea for a distance of nearly 150 miles.*

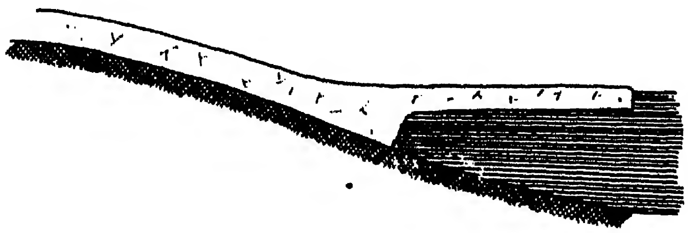


Fig. 73.—Diagrammatic section of a floating Ice-Tongue.

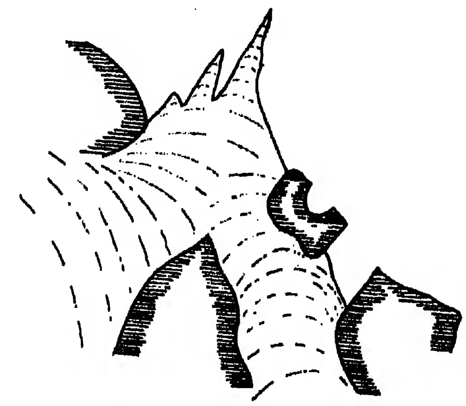


Fig. 74.—Plan of the triple Ice-Tongue of the Murray and Dugdale Glaciers, Robertson Bay.

(Ice-Tongues have been noted in previous Antarctic classifications, being grouped by Gourdon under "piedmont glaciers," and by Ferrar as "piedmonts afloat." It is not clear whether Nordenskjöld would refer them to his type "shelf-ice" or true "piedmont glaciers." Hobbs would apparently class them as "piedmont glaciers".)

Sub-type III (c).—Piedmont-Ice.

The original description of a piedmont glacier, which was created as a special type after the detailed examination of the Malaspina Glacier by American glaciologists, was :—

> "Piedmont glaciers are formed on comparatively level ground at the bases of mountains, where the ice is unconfined by highlands in most directions and has freedom to expand. They are fed by glaciers of the alpine type, which spread out and unite with one another on leaving the valleys through which they descend from snowfields at higher elevations."

This description, with slight modification to extend its scope, will include all true Piedmont-Ice met in the Antarctic.

DEFINITION.—In the present classification, Piedmont-Ice may be defined as *Ice sheets, of which the main original mass was formed by the coalescence of the ice spreading out from two or more wall-sided or valley glaciers, over a comparatively level plain at the base of the mountain slopes down which the glaciers descend.*

Piedmont-Ice may also be formed, under suitable circumstances, by the overflow of the unbroken side of a sheet of Highland-Ice or even the edge of Continental-Ice. It may be left entirely isolated by the cutting off of the supply of ice from above, and will then remain as a stagnant remnant skirting the mountain slopes. The former abundant supply of Piedmont-Ice in the Antarctic has dwindled considerably in recent times.

* From the maps of the Mawson Expedition, it appears to be very doubtful whether the narrow pontoon-like prolongation of the Shackleton Shelf-Ice really is an Ice-Tongue as defined above.

The typical Piedmont-Ice sheet, which is best known to the explorers of the coast of South Victoria Land, is the Butter Point Piedmont to the south of the entrance to the Ferrar Glacier. (Fig. 75, Plate CXXI.)

A much larger example exists to the north of the latter glacier (Fig. 76). This has been named the Wilson Piedmont.

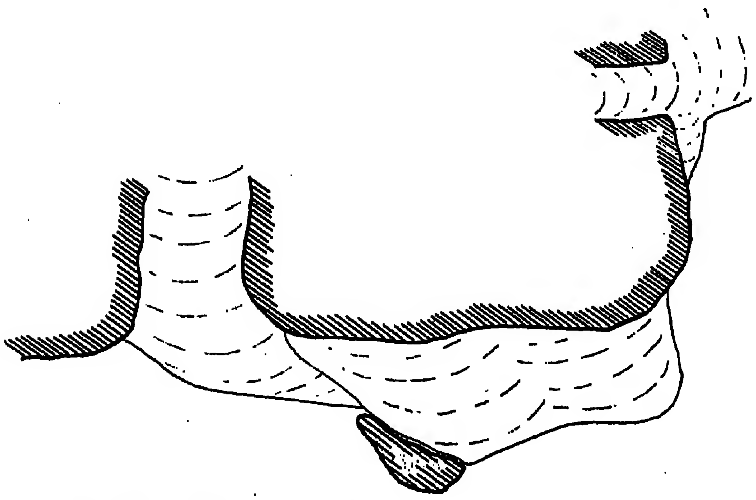


Fig. 75.—Sketch plan of Butter Point Piedmont-Ice.

Before the local decrease in precipitation—assisted possibly by local differential earth movements—largely decreased the supply to the Ferrar Glacier, these two piedmonts were in all probability connected to one another by floating Ice-Tongues protruding from the valley of the latter and from the Taylor Valley to the north.*

The characteristic features of the piedmont are :—(*a*) great length along the coast in comparison with its breadth ; (*b*) usually a multi-lobate seaward end with the projections opposite the principal glaciers by which it is fed ; (*c*) a gentle slope towards the portion

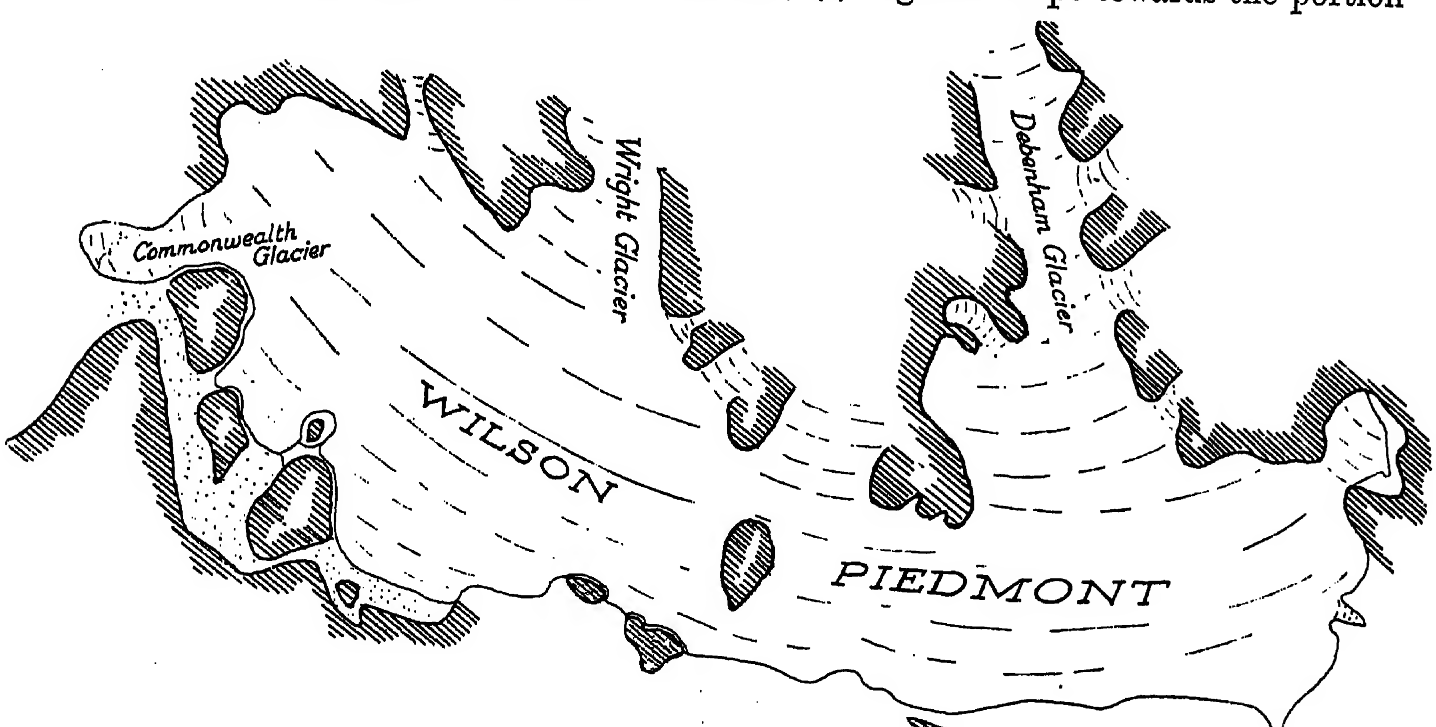


Fig. 76.—Sketch plan of the Wilson Piedmont.

abutting against the shore ; (*d*) an absence of crevasses, except in the areas where the feeding glaciers pour in their fresh supplies of ice.

Piedmont-Ice may also be complicated by the occurrence of floating Ice-Tongues where the more vigorous tributary glaciers have pushed their ice over the edge of the coastal shelf on which the main ice sheet rests.

* For detailed description of these sheets of Piedmont-Ice, *see* Chapter VI.

It may also have its shoreward slope accentuated by an accumulation of snow precipitated or drifted against the mountains to its rear. In the latter case, a considerable portion of the ice supply of the Piedmont-Ice may be derived from the consolidation of this snow,* and the result in such cases may be seen in a more regular outward movement of the ice along its entire face, with a much simpler seaward outline in consequence.

A similar simplicity of outline may result of course from a narrowness of the coastal plain on which the ice is supported. Then, if the ice supply is not sufficient to cause the persistence of floating Ice-Tongues, the ice may break off roughly along the outer margin of the rock shelf beneath it, and a simple cuspate border will result. Piedmont-Ice bordered by the sea will usually be fronted with a steep cliff whose verticality is maintained by the undermining action of the waves. Piedmont-Ice resting on a coastal plain well above sea level will generally have a more rounded face (Figs. 77 and 78).

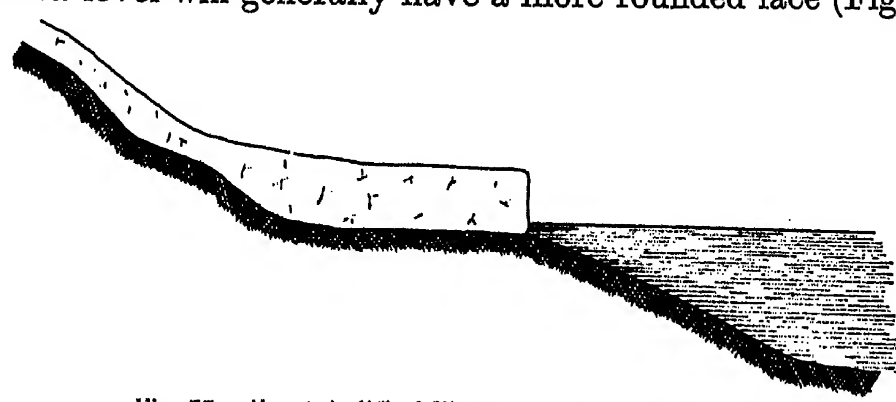


Fig. 77.—Frontal cliff of Piedmont-Ice ending in the sea.

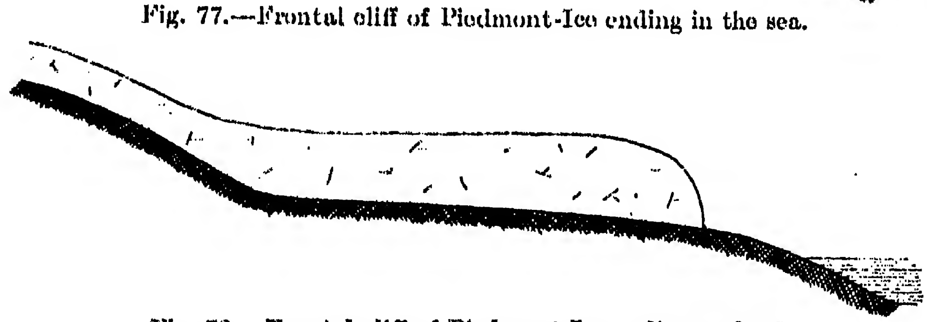


Fig. 78.—Frontal cliff of Piedmont-Ice ending on land.

* This is particularly likely to happen in the case of a shifting of the zone of greatest precipitation from the centre of a glacierised continent towards the coast, or where, as appears to be happening in South Victoria Land, gradual earth movements cause a restriction in the supply of ice from the highlands. The Continental-Ice sheet may be starved of snow while the coastal regions have a comparatively heavy snowfall. In either case, the strong gales so common along a mountainous coast bordering a high cold plateau will tend to prevent the lodgment of the falling snow in the valleys transecting the coastal horst, and the greater portion will be driven into the sea or lie in the lee of the mountains. When, as in the Antarctic, Piedmont-Ice has formed on a suitable coastal plain along the foreland of such a coast, it is easy to imagine circumstances when the main source of supply to such a piedmont would thus be the snow which fell or was drifted on to its shoreward surface. In course of time, such an ice sheet would owe its persistence to an entirely different set of circumstances from those which first caused its formation. This accounts for the somewhat tentative nature of the definition of Piedmont-Ice adopted in the present classification. A certain simplicity of outline and the stratification of the ice are the only visible differences between the ice of the original and secondary piedmont. Neither characteristic is a safe criterion on which to base a differentiation between sub-types. Simplicity of outline may be caused by other agencies, and, in any case, the upper ice of the original piedmont, if it be of large extent and occurs in a country where the snow-line is at or below sea level, is likely to consist largely of stratified snow-ice formed in a similar manner.

Sub-type III (d).—Confluent-Ice.

DEFINITION.—*Ice sheets formed by the coalescence of the Ice-Tongues from several glaciers, but given a definite form and trend by the presence of a land-bar along their seaward edge.*

On a young coast such as that of South Victoria Land, with its numerous islands and prominent peninsulas, it sometimes happens that the extensions from several vigorous glaciers, protruding from the valleys of one portion of the mountain range which borders the coastline, may impinge against rock bars too high for them to override.

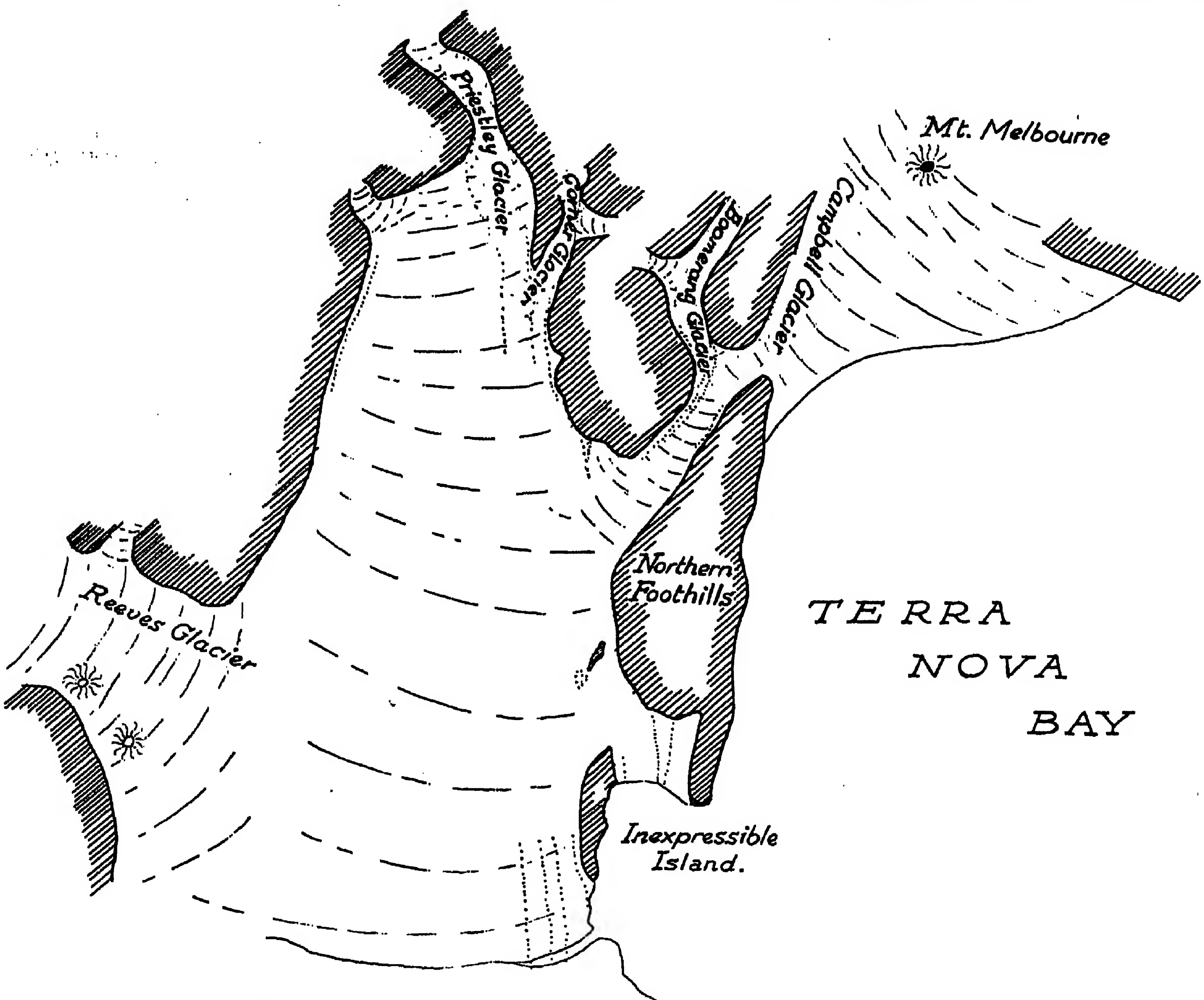


Fig. 79.—Sketch plan of Terra Nova Bay region showing Confluent-Ice.

In such cases, the ice will be deflected and confined and will not assume the typical piedmont shape. The examples are few in number but may be important in size. Since they differ so markedly from typical Piedmont-Ice, both in their shape and in the fact that the coastal plain is not necessary for their existence, it seems desirable to coin a separate name and class them as a distinct sub-type.

The ice sheet is made up of the confluence of several floating Ice-Tongues, and bears the same relation to the individual Ice-Tongue as does Piedmont-Ice to Expanded

Foot-Ice. The outline of the ice sheet in plan is entirely dependent upon its confining boundaries.

A good example of Confluent-Ice is illustrated in plan in Fig. 79, which shows the sheet produced by the coalescence of the Campbell, Corner, Priestley and many smaller glaciers. The contour of the ice is much like that of a free floating Ice-Tongue, if we except the tendency to bank up against the confining walls along its side. Plate CXXII gives a good idea of the surface of the same sheet of Confluent-Ice.

Sub-type III (*e*).—*Avalanche-Ice.*

DEFINITION.—*Ice masses fed entirely by avalanches from the edge of Continental-Ice, Island-Ice, Highland-Ice, or Cwm-Ice, or from the overhanging end of a valley or wall-sided glacier cut off high on a mountain side.*

Avalanche-Ice occurs in all known regions of the Ross Sea area of the Antarctic and, under the name "*Rémanié*," or "reconstructed glaciers," similar forms produced in the same manner have been described from most of the present glacierised land areas. As a rule, the avalanches are absorbed directly into some valley glacier or other ice-form occupying the valley bottom, or the lower ground on which the ice would otherwise fall. In deglacierised portions of the land mass, however—and these, though small in extent, are quite common in South Victoria Land—a special form of typical "talus" or "scree" shape may be developed. The size of individuals is small, but examples are very numerous, and therefore a sub-type to include them seems desirable (Plate CXXIII).

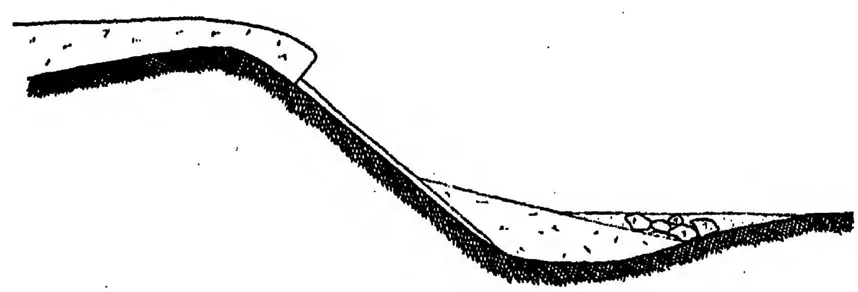


Fig. 80.—Avalanche-Ice and ice apron formed beneath an overhanging valley glacier.

They may be complicated by the occurrence of an "ice-apron" which results partly from the accumulation of drift snow and partly from the refreezing of the thaw-water from the ice sheet or glacier above. An example is figured in Fig. 80 and a photograph of combined Avalanche-Ice and Ice-apron is shown in Plate CXXIV.

TYPE IV.—ICE-FORMATIONS OF THE ZONE OF BALANCED FORCES.

Of all the land-ice forms of the Antarctic Continent, those which have been provisionally separated from the other three types and classed together as type IV are perhaps the most interesting and the most difficult of explanation.

Amongst the ice sheets to be considered under this heading occur some of the largest masses of ice—certainly the largest masses of floating ice—in the world, and they appear to be peculiar to the Antarctic, where alone, apparently, the conditions for their formation and survival now exist. Many of the ice sheets of the "zone of balanced forces" have been examined in some detail by various Antarctic explorers; many of the greatest Polar journeys have been commenced over their surface. They formed the greatest

obstacle to the earlier Antarctic navigators, who relied on ships alone for the prosecution of their journeyings and did not contemplate land travel as a means of increasing the scope of their activity. The two first attempts to penetrate south along the shores of the Ross Sea area were frustrated by their presence. It was this fact that led Sir James Ross to give the name " barrier " to the greatest of all these ice sheets, since it barred his way towards the south for over 400 miles from east to west.

The question of a name or names for this ice sub-type is one which bristles with difficulties. The desire to preserve historical continuity would tend to give a great bias in favour of the original name " ice barrier," were it not for the discordant fact that, what was the " barrier " to the earlier explorers later became the " highway " to more modern travellers. The presence of the Ross Barrier may be said to have lent its aid to the plans of Scott, Shackleton and Amundsen. Had it not occupied the deep indentation at the back of the Ross Sea, this might have been filled, or partially filled, with impenetrable pack, which might have defied the utmost attempts to enter it and to unveil the mysteries of the land behind. The attempts to reach the Pole must then have been made through the medium of the more northerly valleys of the Royal Society Range—probably the Ferrar Glacier valley. No one who knows Antarctic conditions would deny that the longer plateau journey would have added an immense extra handicap to the Polar explorer. " Ice barrier," therefore, while remaining a handy term to the navigator and seaman, for whom it still possesses a marked significance, must be ruled out as a scientific term for use as a generic name for the ice of the coastal zone of the Antarctic.

Nordenskjöld,* in his review of the ice in the Graham Land region of the Antarctic, has adopted the name " Shelf-Ice," which has also been used extensively by other writers. In many ways, the name appeals to the student of ice-forms. It is a simple name, and it suggests at once the shape of the ice-formation, which is usually shelf-like, while, at the same time, it indicates, as the original proposer of the term intended, that the ice sheets of this type lie in the main over the Continental Shelf. It is unfortunate, perhaps, that portions of the ice-formation to which the name was originally given may possibly be formed over projecting rocks and small islands, but if these islands are submerged or insignificant in size, as believed by Nordenskjöld, their presence does not materially affect the question at issue, which is the origin of the ice mass as a whole.

Other local terms have been used for these and other formations of indeterminate origin, notably the " *Westeis* " of von Drygalski† ; but these are of purely local significance, and were used by the men who coined them, to enable them to preserve a conservative attitude towards the origin of the ice, until its extent, formation and characteristics had been studied in more detail and at greater length.

On the whole, Nordenskjöld's designation, " Shelf-Ice," appears to be the most suitable, and the writers can think of no other possessing such advantages as to justify

* O. Nordenskjöld, *loc. cit.*

† E. von Drygalski, *loc. cit.*

the discarding of a name already in general use in scientific memoirs. It is therefore intended to group together all these coastal ice sheets, other than those which definitely fall within the sub-types of type III, as "Shelf-Ice," and to discuss the several probable methods of their formation with particular reference to examples actually met in the Ross Sea area, or to classical examples from other regions of the Antarctic.

The formations grouped together under type IV have been designated as "ice-formations of the zone of balanced forces," because the three factors upon which the main divisions of the present classification are based are each represented in varying proportions at different portions of the ice sheets and at different periods of the year. Supply may be partly through the medium of ice streams from the upland ice sheets; and, indeed, in individual cases, it will be seen that this source of alimentation may be proportionately large. The typical source of supply is, however, from snow precipitated locally, or brought from a distance by the stronger winds. It is even a matter for consideration whether increase in thickness may not take place locally through the downward growth of the sea ice, from which portions of the Shelf-Ice sheets are believed to have grown, or by direct addition of frazil crystals from the water which certainly underlies a great proportion of their area.

Movement is present also, to a great extent in some cases, to a less degree in others. Where accumulation of snow takes place to a considerable depth, a definite outward movement will commence under the influence of gravity, and the ice mass will tend to "thin" itself by advancing outwards wherever advance is possible.

This question will be thoroughly discussed in the chapter dealing with the Ross Barrier, the most interesting and largest sheet of Shelf-Ice met by the Scott Expedition. For the present, it is sufficient to record that movement is by no means negligible, though the slope of the land upon which the shoreward portion of the ice rests may be small and the greater portion of the ice mass may be floating freely in deep water.

Finally, denudation must play an important part in the life-history of any ice mass which has its origin and its existence near, at, and below sea level. The destructive and melting action of the sea severely limits the outward extension of the floating portion. The shoreward portion against the rock slopes of the mountain ranges is seamed with deep thaw gullies and bordered with deep radiation gullies, except where the snowfall is heavy enough to prevent their formation. The whole body of the smaller examples is often traversed and tunnelled by ice streams from the glaciers occupying the deep valleys of the mountains. The surface, if formed of snow, as is usual, is scored by the winds armed with their myriad chisels of drift snow; if of ice, is polished as with emery powder. It cannot be said that denudation normally plays a predominant part in the life-history of these ice-formations, but, certainly, it acts as a very prominent agent in determining their size and their appearance; while, if supply is cut off for any reason, it will soon bring about their disappearance.

The land-ice fringe which is a typical sign of the more advanced phases of the glacial cycle is fast disappearing from the continent. Even in recent times—between

1841 and the present day—the Ross Barrier, to take only a single example, has broken back many miles. Every year, the ice of the coastal zone is retreating in South Victoria Land, and fresh rock islands are appearing to add to the irregularities characteristic of a young coastline of submergence.

Several factors of varying importance can play their part in the building up of Shelf-Ice sheets, but two main methods of formation can be differentiated, according as it is believed that land ice or sea ice formed the principal element of the basal portion of the original formation. There appears to be no doubt that Shelf-Ice can be originally formed with either of these two types of ice as a base, and, although that formed from true glacier ice may be most common and of greatest extent and persistence, the type case to which the name was given is believed by its investigator to have originated chiefly upon sea ice formed in a comparatively land-locked and shoal area.

Sub-type IV (a).—Shelf-Ice formed originally of Land-Ice Extensions with or without Interstitial Sea Ice.

The greater portion of the Shelf-Ice met by British Expeditions seems to belong to this type. It is a logical outcome of the outward growth of a large number of free-floating Ice-Tongues projecting into a confined sea area. At the height of a glacial

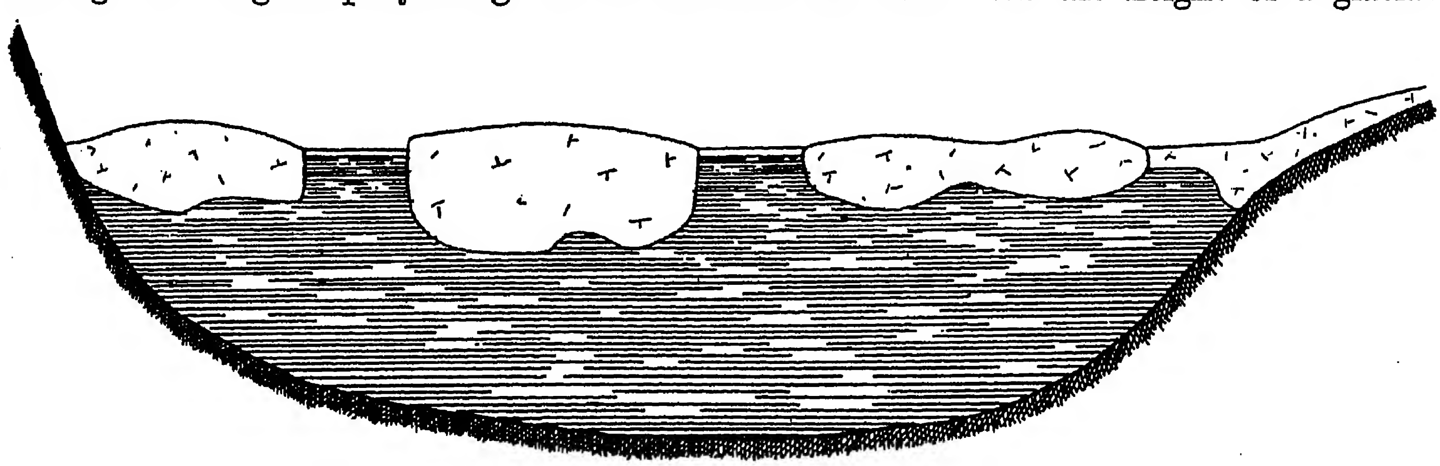


Fig. 81.—Diagrammatic section illustrating the earliest stage in the formation of Shelf-Ice of type IV (a).

period, it will occur still more typically developed as a result of the ordered overflow of the Continental-Ice over the mountain ranges of the coast, wherever these are low enough to permit such a spilling over to take place. In the former case, sea ice may play a subordinate part in the original formation; in the latter case, sea ice will not enter into its composition at all. In either case, the characteristics of Shelf-Ice, as at present understood, do not appear until the contours of the original glacier ice and sea ice have been swamped beneath a heavy accumulation of snow.

If we assume that the ancestor of the present Ross Barrier was formed during the advancing stages of the present glacial cycle largely by the coalescence of Ice-Tongues from the major valleys of the horst, with a certain amount of regional overflow ice from the local Highland-Ice sheets of the foothills, together with interstitial sea ice, a section across it from north-west to south-east in the initial stages of its formation would be as diagrammatically shown in Fig. 81.

The original irregular contours due to differences of level of different types of ice would soon disappear beneath a shroud of stratified ice produced by the recrystallisation of accumulated snowfall and snow-drift, and the ice sheet would then become Shelf-Ice proper (Fig. 82).

If we assume that the recent glacial cycle in the Antarctic never reached an intensity sufficient to cause a complete overflooding of the coastal horst with ice, this ice sheet would not have changed essentially in nature between that time and the

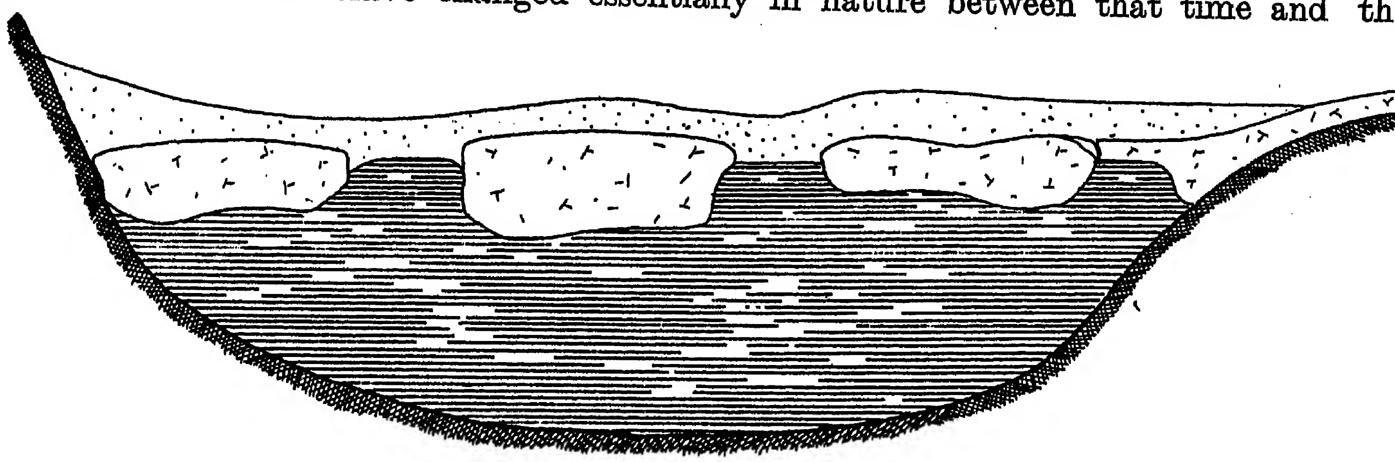


Fig. 82.—Stage 2 in the formation of Shelf-Ice of type IV (*a*).

present day. The relative proportions of glacier ice and snow ice would change, the former first increasing with the greater flow of ice from the highlands as the maximum of the ice age approached, and then decreasing as the glacierisation of the land became less intense.

From an early stage in the history of the ice mass, the accumulation of snow would generally be sufficient to press the original sea ice downwards and outwards to a zone where melting from beneath would soon eliminate it as an element of importance. Its original *rôle* as a raft for snow would now be fulfilled by the snow which had itself collected upon it in earlier times.

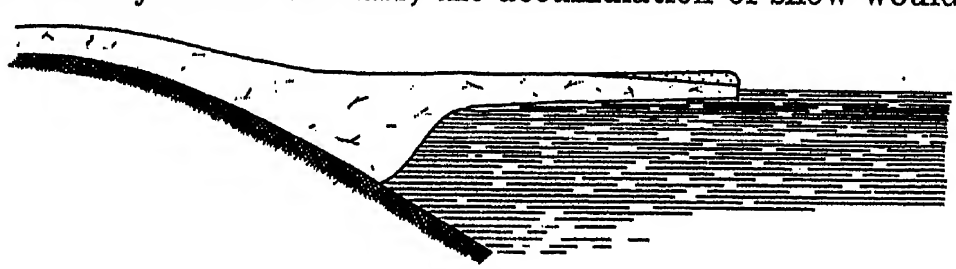


Fig 83.

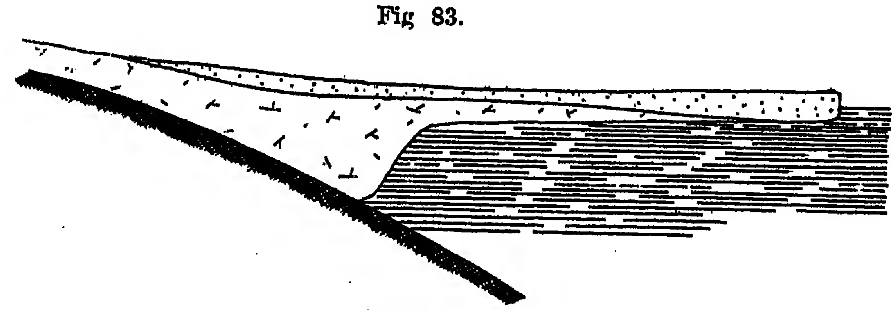


Fig. 84.

Diagrammatic sections through Shelf-ice of type IV (*a*) opposite a valley. The greater volume of glacier ice poured down the valley causes this type of ice to assume a greater importance in the ultimate composition of the Shelf-Ice than elsewhere.

As time progressed, and the proportion of snow to ice increased, the glacier ice in its turn would be swamped beneath the accumulation and entirely obliterated, except where the decreasing valley glaciers of the horst were still vigorous enough to plough their way into the rear portions of the Shelf-Ice. Figs. 83 and 84, which are sections

from base to snout of a sheet of Shelf-Ice of this type opposite a tributary glacier, and Figs. 85 and 86, which are similar sections opposite one of the higher portions of the coastal mountain wall, will serve to indicate diagrammatically these stages in the formation of the sheet. As the original source of glacier ice is left behind, the proportion of snow to ice increases, the majority of the ice is removed by melting from below, and, finally, at the sea face no true glacier ice remains at all. We have here a stratified mass of snow-ice of such small density that the proportion above water is as much as one-fourth or one-fifth of the whole.

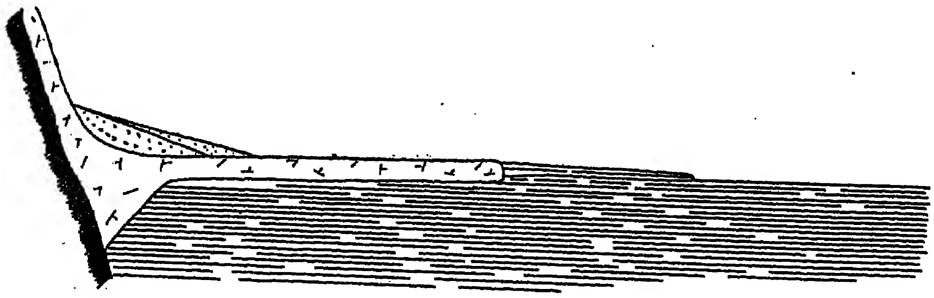


Fig. 85.

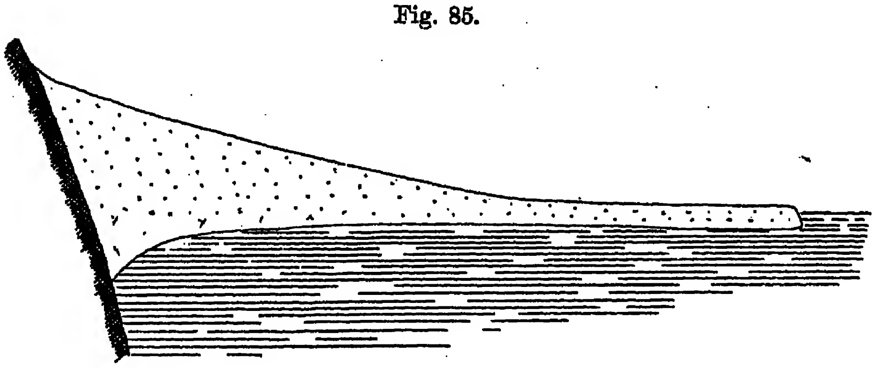


Fig. 86.

Sections through Shelf-Ice of type IV (*a*) opposite one of the higher portions of the coast. Shows the elimination of glacier ice and sea ice from the ultimate composition of the Shelf-Ice.

Icebergs calving from such a face will consist of stratified snow-ice alone. That this is the case with the bergs forming off many bodies of Shelf-Ice at the present date, is shown by the fact that most Antarctic icebergs met in the Victoria Land region have this comparatively large proportion of their mass above sea level, and, when overturned in the course of their denudation, the same stratified ice of low specific gravity can be seen throughout the lowest layers.*

The chief characteristics of such a sheet of Shelf-Ice are :—

(1) A shape conforming to the boundaries of the indentation of the coast which has favoured its formation, or, if it has survived in the lee of a straight coastline, as sometimes happens, a simple, almost straight, seaward edge ;

(2) The fact that its seaward end is usually floating freely in deep water ;

(3) Limiting cliffs at its seaward face, which are perpendicular, as in the floating Ice-Tongues or Piedmont-Ice which fronts the sea ;

(4) Broad undulations where it abuts against obstacles in the shape of rock islands ;

(5) Distinct pressure ridges and orderly systems of crevasses in the neighbourhood of the major tributaries which feed it.

Its upper surface, with the exception of the minor irregularities mentioned above, will sweep gently down until the seaward edge of the stranded portion is reached, and from there will continue as an almost horizontal plain to the seaward face. Broader undulations may mark the presence of well-defined tributaries, but these rises will tend

* The ice of many Antarctic glaciers is beautifully stratified, but close examination will show that it is of greater density and larger grain than typical Shelf-Ice.

to be masked to a considerable extent, the depressions between them being filled with drift snow. On the other hand, when the accumulation of snow is at or near its maximum, the areas where the principal glaciers pour in their quota of ice may be markedly lower than the remainder of the shoreward portion of the sheet, since the valleys tend to concentrate the wind and thus to increase ablation, remove precipitated snow, and prevent accumulation of drift.

Sub-type IV (b).—Shelf-Ice originally formed mainly or entirely by the Accumulation of Snow upon Sea Ice which has persisted for several Seasons.

The area of Shelf-Ice occurring in the Ross Sea region which can definitely be assigned to this cause is negligible. It is probable, however, that an ice-formation sighted in the Discovery Expedition to the east of King Edward VII Land may belong to this category, while von Drygalski has claimed a similar origin for his "*West-Eis*," and Nordenskjöld has ascribed a large ice-formation to the same agency. In addition, certain observations of the British Antarctic Expeditions have proved the persistence of small areas of sea ice in sheltered or otherwise favoured positions for several years together, and there appears no reason why, given favourable seasons, this persistence should not continue on a much larger scale as regards both space and time.

The principal enemies to the persistence of sheets of sea ice are tides, swell, winds, advancing Ice-Tongues, summer thaw and ablation, pressure, changes of temperature, etc., and the work of all these is studied in some detail in other chapters of this memoir. Normally, the fast-ice* sheet is weakened during the winter by the formation of a network of cracks due mainly to the last two factors. Its disintegration is hastened in summer by thaw and swell. Winds speedily carry northwards the loosened portions. Tide-cracks and the thrust of advancing Ice-Tongues prevent that close adhesion to the land which might otherwise defy the power of the remaining agents of destruction.

Still, situations do occur where the destroying forces are, for various reasons, shorn of a considerable portion of their power, and, where the fast-ice does remain, it increases steadily in thickness and also, if the situation is favourable, becomes heavily snow-covered. Favourable situations for its persistence are deep land-locked bays unoccupied by advancing land-ice formations. If such bays are on a lee shore, the conditions are still more suitable, for, though the wind exerts a considerable "drag" on a sheet of level fast-ice, the lee prevents the rise of a heavy sea and so diminishes the mechanical effect of the wave action. Examples of such situations where fast-ice has remained for several seasons may be cited at the head of McMurdo Sound, both near the "Pinnacled Ice" to the west of the sound and at Hut Point. These are, however, the only striking instances which have been noted along the whole of the considerable stretch of South Victoria Land which has been studied by the British Expeditions for several years. The area affected is very small, and the accumulation has been limited, in one case to two seasons, and in the other to three or four at most. Still, the fact remains that the persistence has occurred, if only for a limited time, and in a localised area.

* Unbroken sea ice.

A series of abnormally cold calm years might at any time cause a greater extension of this semi-permanent sea ice in various bays and nooks along the coast. If such a sheet were once formed and firmly established and much increased in thickness by the accumulation of snow from above, it would, given sufficient snowfall, assume the characteristics of Shelf-Ice, and would become " sealed " to the land by the cementing of the tide-crack. It would then be likely to persist until the supply of snow was insufficient to enable it to maintain itself against the never-ceasing attacks of the sea. Indeed, given sufficient precipitation, it might grow in size out of all proportion to the area of the original piece of fast-ice on which it was based and to which it owed its formation.

The coast of South Victoria Land, a young steep faulted coast, with deep water close off shore and with the majority of its islands swamped in other coastal forms of land ice, is not suitable for the persistence of sea ice, and it is not surprising that the known cases are few and far between. On the coast of the Graham Land Sector of the Antarctic, on the other hand, the land is in places bordered by groups of islands, and these are interspersed with shoal areas which would also, by the collection of stranded icebergs, afford good holding ground for sea ice.

Such a coastline affords an ideal situation for the accumulation of sheets of Shelf-Ice of the type now under consideration. Wave action over such shoals would be reduced to a minimum, the numerous islands and islets would combine with a somewhat irregular main coastline to shelter the fast-ice sheet, once it had grown to any thickness. Along a coast of this description, the conditions are ideal for the formation of semi-permanent sea ice, and it is from this coast that Nordenskjöld's type example of Shelf-Ice is taken. The Shelf-Ice of King Oscar Land appears to have been formed on semi-permanent fast-ice which had persisted for several years over a shoal, and had also possibly been held in position by emerged peaks in the shoal area. On this, snow accumulated until the original sea ice of the sheet had been depressed far below the surface, and the lower portions of the resultant Shelf-Ice had first grounded on the salient points of the shoal, and had then grown downwards until firmly anchored. Further growth from below may or may not have helped to achieve this result.

The undulating surface of the top of the Shelf-Ice, as described, would suggest that it is now conforming fairly well to the major irregularities of the bottom. The formation of such a sheet of Shelf-Ice violates no law of nature, and, once it has been formed, its persistence or disappearance will depend entirely on the ratio of alimentation to denudation.

This is certainly the most satisfactory explanation for the Shelf-Ice of King Oscar Land and, given a suitable coastline and suitable climatic conditions, this method of growth might give rise to ice sheets in number and extent limited only by the areas of shoal water available.

Suitable anchoring points in the form of emerged rocks or islets would appear to be essential to the formation of ice sheets of this type, but the question at once arises whether these could not be replaced by icebergs stranded around the edges of the shoal.

It is upon this theory that von Drygalski has founded his explanation of the type of ice he has denominated "*West-Eis*," though Phillippi believes that this ice is a much weathered portion of what he calls "Inland Ice" and he considers it to form actually a portion of the margin of the Antarctic Continental-Ice sheet.

A similar series of shoals and groups of islands and stranded bergs is believed to be the nucleus of the heavy fast-ice off King Edward's Land. This has, however, only been glimpsed from a passing ship, and it would be unwise to theorise upon its origin until more facts are available.

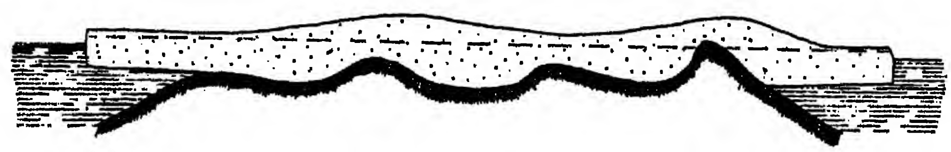


Fig. 87.—Diagrammatic section through Shelf-Ice of type IV (*b*).

It is sufficient for the present to state that we believe that sheets of Shelf-Ice of considerable extent may be, and have been, formed in the way outlined above, and must be recognised as a distinct sub-type. An ideal section through Shelf-Ice of type IV (*b*), is given in Fig. 87. It is in effect a mass of Island-Ice over a submerged island. A similar section of a land-ice formation based on a sheet of fast-ice in a bay is shown in Fig. 88. This type might not easily be distinguished from Shelf-Ice of type IV (*a*) into which it would merge by an increase in the proportion of basal material provided by glaciers and a decrease in that consisting of sea ice. In practice, however, there should be a difference between the two types, since the presence of even one small but vigorous Ice-Tongue in the back of the bay in which the fast-ice formed would be sufficient to ensure its annual disruption and therefore definitely to prevent the formation of Shelf-Ice by this method.

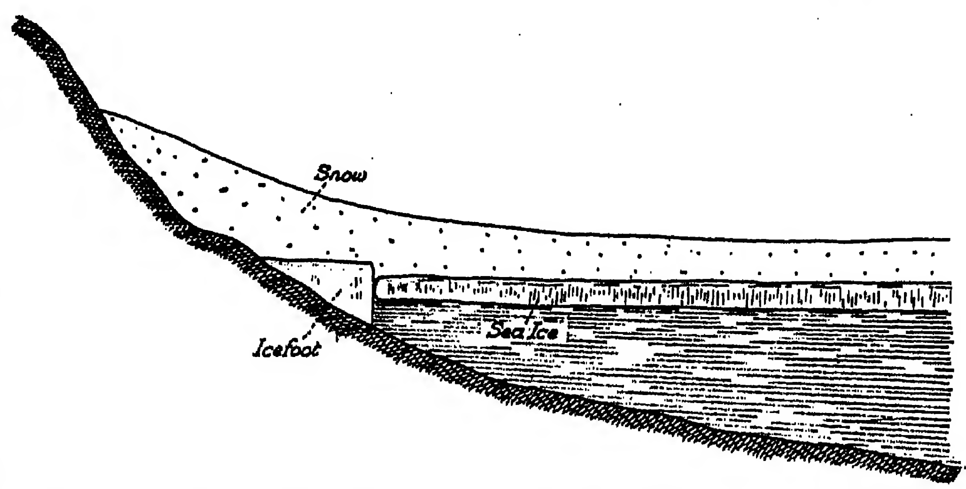


Fig. 88.—Diagrammatic section through a sheet of Shelf-Ice such as might be formed by the accumulation of snow upon semi-permanent sea ice at the back of a bay or in lee of a sheltered coast.

(6.) Discussion of Previous Classifications and Comparison with the Present One.

A comprehensive comparison between the principal previous classifications is afforded by a study of Table VII. It will be seen from the table that the tendency has been towards an increase in the number of types and towards an abandonment of the place-names which characterised the earlier classifications.

Both of these reforms are steps in the right direction. As research into the mode of origin of different ice-forms has proceeded, a widely different genesis has had to be

admitted for many which had been grouped together under one heading in previous classifications. Sub-types have had to be created, if the modern classifications were to convey any idea of genetic relationship.

As regards the question of locality names, which have crept into some of the more modern classifications, and are still largely used in books not necessarily devoted to the study of glaciers alone, it is considered that it would be distinctly better if these labels, based on the countries in which these types of glaciers were first studied, could be entirely dropped. The words "Alpine," "Norwegian," "Alaskan," "Greenland," are distinctly misleading, for change of climate may cause the typical development of any form of land ice in any of the present glacierised regions. At the same time, an increase of climatic severity might develop many ice-forms in lands which are at present entirely devoid of glaciers of any kind.

For this reason alone, it appears to the writers that place names are unsuitable for application to land-ice types. For the same reason, exception is taken to the adoption of the sub-types "Arctic" and "Antarctic" as sub-divisions of Nordenskjöld's "Inland Ice," the more especially as the latter himself remarks that "Arctic" types do occur in that region of the Antarctic of which he has personal knowledge.

An additional argument against the retention of the old place-names is afforded by the fact that some of them at least have come to possess an entirely different significance in the minds of different writers. This is well displayed by the following comparative definitions of "Alpine," "Norwegian" and "Greenland" glaciers.

Alpine Glaciers.

HEIM.—*Beim Alpentypus ist die schärfste Individualisierung der einzelnen Gletscher ausgesprochenen.*

WERTH.—*Muldenfirn und zugehöriger Talgletscher.*

FERRAR.—Glaciers of Alpine type, valley glaciers, drain small intermontane basins (*firnmulden*), seldom advancing far from their mountain sources; they never reach the sea.

These three definitions agree fairly closely, but *per contra* we have the following definition by Hobbs :—

HOBBS.—Alpine glaciers are sheaves of small glaciers or glacierets which start out from the secondary scallops of the mature cirques. They are wholly included within the mother cirque . . . in reality the glaciers of the Alps, far from occupying valleys, do not even fill the mother cirques at the valley heads.

Norwegian Glaciers.

HEIM.—*Beim Typen Norwegen fehlen die firnschneiden entweder ganz oder sie sind doch meistens nur unscharf ausgebildet, so dass die Nahrgebiet ein vielfach zusammenhängendes gemeinsame Firnreservoir ist.*

WERTH.—*Einheitlicher plateaufirn und einzelne getrennte Talgletscher.*

FERRAR.—Glaciers of Norwegian type consist of streams of ice flowing down well-defined valleys (fjords) from a large firnfield.

Greenland Type.

HEIM.—*Beim Typus Grönland endlich sind auch die Eisstrome keine Individuen mehr, sondern bilden eine zusammenhangende Flut, die erst im aussersten Rande sich in Auslaufe gabelt.*

WERTH.—*Einheitlichen plateaufirn und zusammenhangende Gletschermasse.*

FERRAR.—Glaciers of Greenland type or ice-streams drain an ice-sheet and end in the sea.

An examination of the definitions will reveal several grave discrepancies between them, and, if the argument of historical continuity in nomenclature is considered to carry sufficient weight to justify the retention of the terms (which the writers do not think), it is obvious that standardisation is necessary.

To-day, many authors will not accept Alpine glaciers as true valley glaciers, but claim, as does Hobbs, that the majority of them do not extend into valleys at all, but have their beginning and end within the limit of a cirque which formerly was the head of a large valley glacier. From an examination of the maps of Switzerland it would appear that true valley glaciers—as defined in the present paper—do exist there, but that the majority are of the type defined by Hobbs.

The cause of the differences between the above definitions of Norwegian and Greenland glaciers is easily recognised. The original workers—Heim and Werth—consider together gathering ground (firnfield) and diffluent (glacier), while Ferrar restricts the names to the distributaries themselves. The same objections can be urged against these names as applied to Alpine glaciers.

With the classifications of Gourdon and Nordenskjöld, the present attempt has much more in common. Both of the former have adopted the factors of supply and movement as the chief basis of their scheme, and the sub-types of Nordenskjöld, in particular, agree closely with those suggested here. Reasons have been given above for the exception taken to the terms "Arctic" and "Antarctic." The term "icefoot" or "icefoot glacier," respectively, adopted by these writers for a special type of ice-form derived from snow-drifts is objected to, because it ties down the sub-type to a special restricted zone of the land mass under consideration.

Actually, Snowdrift-Ice may occur in any sheltered position on a glacierised land. With these two exceptions, the difference between the classifications is one of presentation and arrangement rather than of more essential characteristics. The definitions now proposed agree especially closely with those of Nordenskjöld.

The classification given by Hobbs in his "Characteristics of existing Glaciers" possesses the merit of being the first classification to be based upon a comprehensive review of the ice-forms of the chief glacierised countries of the world. Hobbs, however, while claiming to have taken "alimentation" as his chief deciding factor, appears to give an altogether disproportionate importance to the relationship between the ice-formation and the land upon which it rests. The result has been a multiplication of types in those forms which are characteristic of the closing stages of the recession period of a glacial cycle, and the lumping together of all the major ice-formations of the world

under a single heading "Ice-cap type." The classification thus gives an altogether wrong impression of the relative importance of the different ice-formations.

It is unfortunate that, although a considerable portion of his book is devoted to an illuminating summary of recent work in the Arctic and Antarctic, so little importance has been allotted to these regions in a classification intended to be of universal application.

The outlet glaciers of the Continental-Ice of the Antarctic and of Greenland do not appear to fall easily within any of his types, for they certainly do not agree with his definition of "dendritic" or valley glaciers. Amongst the examples given of this type, not a single Antarctic glacier is cited, while the only representatives from the North Polar regions are two from Alaska, which is not a typically glacierised Polar country.

The meaning given to the term piedmont, by Hobbs, also appears to be somewhat unsatisfactory, for the typical features of Piedmont-Ice are all associated with the debouchment of the streams of ice upon the foreland at the base of the mountains. In different situations, the same ratio of supply to denudation will give quite other results. Piedmonts, as typically developed in Polar countries, also owe a considerable portion of their bulk to other sources. Hobbs' type "piedmont glacier" might be considered to include glaciers draining highland and upland ice-sheets, were it not for the fact that the greater portion of such glaciers do not form piedmonts. Shelf-Ice, though discussed at some length in the later portion of the book, is not referred to at all in the chapter dealing with classification, and thus the most interesting and one of the most important types of Antarctic land ice is ignored.

The various types of mountain glaciers in descending order of alimentation as recognised by Hobbs are useful minor sub-divisions of the ice-formations in the later stages of the glacial cycle, though the type "tidewater glacier" would appear to merit a position higher in the scale. It is not considered, however, that in a universal classification of land-ice forms they deserve the relative importance that they have been given.

Finally, the type of ice-form called by the writers "snowdrift-ice" and by Nordenskjöld and Gourdon "icefoot glaciers," has been named by Hobbs the "nivation" type of glacier, after the method by which it is claimed that the snow-drifts exercise a deepening action upon the shallow depressions in which they lie. The term adopted here is, however, preferred, since the process of "nivation" certainly has no important bearing on many of the Snowdrift-Ice masses of the Antarctic. In individual cases, the action described under this term does take place to some extent, but it is significant that, although hundreds of thousands of such drifts occur at low levels in exposed Antarctic lands, yet they never appear to deepen their depressions to any great extent, certainly not to the extent of entrenching themselves in true cirques or cwms.*

Certainly, at low levels in the Antarctic at the present time, permanent Snowdrift-Ice appears to exert a predominantly protective influence on the ground on which it

* The question will be discussed at some length in a short Memoir on the Physiography of the Robertson Bay region of South Victoria Land, by R. E. Priestley, published as one of the Reports of the present Expedition.

lies. Where the drifts are not permanent, their effect must be much as in the examples quoted by Hobbs from a country of warmer climate. The term Snowdrift-Ice is preferred to "nivation glacier" as being of more universal application, and as expressing better the salient characteristics of the ice-formation.

For the present classification, it is claimed that the types are based upon the three most important factors involved in the glacierisation of a country, while other factors less important, but sufficient to cause essential modification of ice-forms, have been called in to assist in the delimitation and definition of sub-types. The classification is comparatively simple and is of universal application.

Practically all important forms of land ice existing on the face of the globe should fall naturally into one or other of the classes which have been arranged in accordance with the natural sequence of events in a cycle of glacierisation. The types are few in number and well differentiated. If further sub-types are required for the purposes of physiography, they can easily be superimposed on the present main types by using the factor of land relief to a greater extent than has been done here. The classification is based in the main upon the continent which is at present subjected to the process of glacierisation to a greater extent than any other, and, therefore, as can be seen from the short description of the glacial cycle at the commencement of the chapter, upon that land mass which is likely to contain the maximum number of types. In South Victoria Land, everything can be seen, from the Continental-Ice sheet of the Inland Plateau to the dry valleys of the coast where ice is not. Every type of land-ice form from Snowdrift-Ice to Continental-Ice, and from the largest known valley glacier in the world to decadent "ice-slabs," has come under the notice of one or other of the writers.

CHAPTER VI.

ICE-FORMATIONS CHARACTERISTIC OF AN ADVANCED STAGE OF THE GLACIAL CYCLE.

In this chapter, certain ice-formations which are characteristic of an advanced stage in the glacial cycle will be described, with special reference to Antarctic examples. These fall naturally under the following headings :—

1. Continental-Ice, Highland-Ice and Island-Ice.
2. Piedmont-Ice and Confluent-Ice.
3. Ice-Tongues.
4. Shelf-Ice.

Much has been written descriptive of ice-formations of other types observed in all parts of the world, and it does not seem necessary to treat these types as fully as those which are dependent for their existence on more favourable conditions than are found in regions outside the polar circles.

It must not be inferred that the types which are to be described in some detail are not, some of them, developed outside the polar circles, but that their *full* development demands a conjunction of physical and meteorological conditions which is only met, at present, within the polar regions.

Continental-Ice.

Though our information regarding the interior of the Antarctic Continent is still far too scanty, sufficient is known to enable us to say with certainty that it is capped by the largest mass of Continental-Ice on the surface of the globe. With the exception of a narrow strip at the border, the whole of the elevated portion of the continent is probably covered with an almost unbroken ice dome. Its area can hardly be much less than 5,000,000 square miles, that is, comparable in size with the continent of Europe.

Very little of this enormous plateau has been actually traversed, and our information regarding the ice sheet is entirely superficial. It was first traversed by Captain Scott in the Discovery Expedition, a journey being made for more than 150 miles in a westerly direction from the head of the Ferrar Glacier, a distributary debouching into McMurdo Sound.*

Shackleton,† in the summer of 1908–9, ascended the Beardmore Glacier, an outlet from the Plateau to the Ross Barrier, and proceeded in a southerly direction to latitude 88° 23′ S., where, at a height of nearly 10,000 feet, he was forced to turn back

* 'Voyage of the "Discovery."'

† 'Heart of the Antarctic,' vols. 1 and 2.

in his attempt to reach the South Pole. In the same summer, Professor Sir Edgeworth David* led a party to the South Magnetic Pole in latitude 72° 25′ S., longitude 155° 16′ E., involving a journey of about 150 miles on the Plateau from the head of the Reeves Glacier.

In the summer of 1911–12, Amundsen reached the South Pole,† followed one month later by Captain Scott,‡ while in the following summer the Plateau was ascended in about 140° W. longitude by parties of Mawson's Expedition.§

Many hundred miles of toilsome and dangerous travel were involved in these journeys, but it cannot be too strongly insisted that our knowledge is still only local in character, and entirely confined to a knowledge of the *surface* conditions in the height of summer. In some cases the information gleaned is not yet accessible, and the adverse physical conditions attending sledge journeys on the Plateau militate against the making of exact scientific observations. The warmest month of the year, December, had a mean temperature in 1911 on the Polar Plateau of — 8·6° F., the mean temperature in the following January being — 18·7° F.

As has been pointed out before, the formation of a sheet of Continental-Ice demands, above all, an adequate supply of snow. This must be greater than the loss by ablation from the surface and the loss by movement of the ice to lower levels, in addition to the practically negligible loss of ice due to melting on the surface or within the body of the ice sheet. The latter condition is clearly fulfilled over practically the whole of the Antarctic Continental-Ice, and we have therefore only to examine the conditions of yearly snowfall and yearly ablation|| on the surface of the sheet, together with the rate of movement to lower levels. Simple as the problem appears, no answer can be given as to the magnitude of either the yearly snowfall, the yearly ablation, or the yearly rate of movement. It is true that the Plateau has only been visited in the summer months; but, even were a well-equipped station erected thereon and maintained for a long period, measurements of snowfall, ablation and movement could hardly be obtained. Measurements of snowfall and of ablation are almost impossible to make; measurements of the movement of the ice sheet could only be obtained by astronomical observations over long periods. Since a sheet of Continental-Ice exists, we can only say that conditions in the past were favourable to the formation of such a sheet. Our information as to whether the sheet is increasing in thickness, or decreasing, must be derived from the natural tide gauges formed by land masses where they abut the Plateau. The evidence from these tide gauges all point to a recent greater thickness of the Continental-Ice, but afford little evidence as to how much greater this thickness was. An ice sheet of greater thickness means the development of greater pressure against obstacles preventing its movement. This causes the ice to ascend the slopes of the obstacles to a greater extent than would otherwise be the case. Thus, Mount Darwin, at the head

* 'Heart of the Antarctic,' vols. 1 and 2.

† 'The South Pole,' vols. 1 and 2.

‡ 'Scott's Last Expedition,' vol. 1.

§ 'The Home of the Blizzard.'

|| The word "ablation," as used in this memoir, includes chiselling by drift.

of the Beardmore Glacier, was recently overrun by the Continental-Ice sheet, but what increase in the present general thickness of the ice would be necessary to achieve this result is quite unknown. It is of considerable interest to note that the mountains which fringe the Continental-Ice in the Ross Sea Sector are often fairly free from snow. Parts of Buckley Island at the head of the Beardmore Glacier furnish a good example of this, showing that (locally, at least) ablation *on a rock surface* may exceed precipitation. One cannot, however, argue from this that ablation exceeds precipitation on the snow surface of the Plateau.

Such evidence as we have, in fact, points quite the other way. The surface of the Plateau in the neighbourhood of the South Pole is covered with soft snow, even in the middle of summer. The surface of the Beardmore Glacier is ice, the air-content of the ice increasing as the Plateau is approached. There are occasional heavy snowfalls in summer, particularly on the lower reaches of the glacier,* but the snow surface rapidly disappears, part of this change being doubtless due to conversion of snow into ice, but much of it undoubtedly to heavy ablation. It does not follow that ablation necessarily exceeds evaporation on the Beardmore Glacier, but it appears to us that the surface conditions on the Polar Plateau can only be explained if deposition here exceeds ablation.

There seems no doubt that the meteorological conditions on the Plateau are essentially anticyclonic in type, and it is difficult to reconcile these two facts, as anticyclonic conditions seem to demand a poverty of precipitation.

Before dealing in detail with this point, it is necessary to review the observations which have been made on wind direction and force. These observations are discussed by Dr. Simpson in vol. 1 of the Meteorological Report of this Expedition. It will be seen (p. 105) that the curve showing frequency of winds of different velocities on the Polar Plateau is of the Cape Evans type, the distribution of velocities being essentially anticyclonic, and differing from the Framheim type† by the superposition of a very frequent wind of about 12 miles per hour. Calms are, in fact, about as frequent in the two summer months for which observations are available (December and January) as winds of about 12 miles per hour. On the Polar Plateau (p. 146), practically all the *high* winds come from directions between S.S.E. and S.S.W., these directions being those from which the low-velocity winds blow.‡ On the Plateau west of the Ferrar Glacier (p. 145), the most frequent wind direction on the "Discovery" journey was from W.S.W., a strong southerly component being superposed during blizzards. The sastrugi confirm the above observations as to blizzard wind directions.

Even in the summer months, the Plateau is undoubtedly a bad place for travelling, particularly when one comes to consider the low temperatures experienced, even during winds of blizzard strength.

* The phenomenon of heavier snowfall on the lower reaches seems to be common to all such valley glaciers in the Ross Sea quadrant.

† In this type a "calm" is the most frequent wind, and the frequency of other winds is less the greater the velocity of that wind.

‡ South being here defined as "parallel to the 160th East meridian."

Much additional information regarding Plateau temperatures will be available when the meteorological reports of other expeditions are published. There seems, however, sufficient evidence already to show that the temperature conditions in the summer 1911–12 were not *very* abnormal.*

As might be expected, in view of the almost constant altitude of the sun at this latitude, there is no great difference between "day" and "night" temperatures on the Polar Plateau. There was, however, a fall of 10° F. in the mean temperature in January, 1912, compared with the previous month, indicating a most marked correlation between temperature and isolation.† The comparatively low mean temperatures are due, not to the high latitude, but to the great altitude of the Polar Plateau.

The sudden fall in temperature in January is paralleled by an even sharper fall on the Ross Barrier at a somewhat later date (commencing in the latter half of February), and this fall was also noted by Shackleton. A glance at the curves on p. 84 of the Meteorological Report makes it quite clear that if Captain Scott's journey to the Pole had been commenced a month earlier, he would have avoided the appalling temperature conditions‡ met by the Polar Party on its return journey over the Ross Barrier.§

It is clear in any case that, if the temperature difference between the Barrier and the Plateau, which is due chiefly to the great difference in height, exists equally in summer and in winter, the winter temperatures on the Polar Plateau must oscillate about – 70° F. as a *mean*.

Professor Hobbs explains the wind circulation of the Antarctic Continent and of Greenland as the result of the cooling of the surface air by contact with the cold elevated snow-covering of the Plateau, the cold air then streaming down along the line of greatest slope at each point. He has also proved experimentally that a small cooled dome-shaped surface will indeed cause such a circulation. Such an explanation is adequate to account for the observed air circulation during the winter, but, if Hobbs' explanation is correct, it is not easy to see how the snow surface can cool the air in contact with it *during the summer*,|| when radiation from the sun is comparatively intense. It may also be pointed out that, in December and January, the wind blows definitely uphill in the neighbourhood of the South Pole. Too much stress should, however, not be laid on this point until more information is available regarding the height of the Plateau beyond the Pole.

We are now in a position to consider the problem of relative snowfall and ablation on the Plateau in somewhat more detail, bearing in mind the fact that the evidence shows that the Plateau surface is by no means level. Scott, Bowers and Shackleton

* The summer temperatures seem to have been lower than those of the preceding year, judging by the curve shown in Fig. 175 of the Appendix.

† There is every probability, however, that the temperatures in November are quite possible for sledging on the Plateau.

‡ Low temperatures appreciably increase the labour of sledge-hauling.

§ The month's delay was due to a desire on Captain Scott's part to improve the chances of the ponies.

|| This point has been more fully discussed in Chapter I.

all unite in pointing out that, on the journey towards the Pole, the surface on the top of undulations of the Continental-Ice was usually hard wind-driven snow, while soft deep snow lay in the hollows in the lee of the crests. Within a few miles of the Pole, however, both hollows and crests were covered with this soft deep snow.

One cannot do better than quote Bowers' entry on this point in the Meteorological Log :—

> "Within 120 miles of the Pole, the sastrugi seem to indicate belts of certain prevalent winds. These were definitely S.E.ly up to about 88° 30′ S., where the summit was passed, and we started to go somewhat downhill toward the Pole. An indefinite area was then crossed, with S.E.ly, S.ly and S.S.W.ly sastrugi. Later, in about 89° 30′ S., those from S.S.W. predominated. At this point also, the surface of the ice cap became affected by undulations running more or less at right angles to our course. These resolved themselves into immense waves some miles in extent, with a uniform surface both in hollow and crest. The whole surface was carpeted with a deposit of ice crystals which, while we were there, fell sometimes in the form of minute spicules and sometimes in plates. These caused an *almost continuous display of parhelia.* The flags left a month previously by the Norwegian expedition were practically undamaged, and so could not have been exposed to very heavy wind during that time. Their sledge and ski tracks, where marked, were raised slightly, also the dogs' footprints. In the neighbourhood of the S.P.* Camp the drifts were S.W.ly, but there was one S.S.E. drift to leeward of tent. They had pitched their tent to allow for a S.W.ly wind. For walking on foot, the ground was all pretty soft, and, on digging down, the crystalline structure of the snow was found to alter very little, and there were no layers of crust such as are found on the Barrier. The snow seems so lightly put together as not to cohere, and makes very little water for its bulk when melted. The constant and varied motions of cirri, and the forming and motion of radiant points, show that in the upper atmosphere at this time of year there is little or no tranquillity."

There seems little doubt that the presence of the undulations on the Plateau surface exercises a considerable effect in locally modifying the wind movements and in causing turbulent motion in the atmosphere.

It is clear that the greatest deposit of snow takes place in the lee of the crests of the undulations and that, at least to the north of the Plateau summit, little, if any, snow remains on the crests themselves. The tendency of the wind is, therefore, to make the surface more level and at the same time to move large quantities of snow to more northern latitudes. The fact that the undulations remain pronounced seems to prove that they are caused by an appreciable outward movement of the Continental-Ice.

We are of opinion that the excess of snowfall over ablation must be quite small to the north of the summit. The conditions to the south of the summit seem to be

* South Polar.

somewhat different. The soft surface may be due to a greater precipitation following the forced rise of the air travelling against the slope of the Plateau, though it is possible that part of this softness of surface may be due to a lesser wind velocity in this region. There is no evidence to the contrary. Certainly, one would not expect any noticeable hardening of the surface at the temperatures observed in this region, except through wind action. Amundsen states* :—

> "Often on this part of the Plateau to the south of 88° 25′, we had great difficulty in getting snow good enough, *i.e.* solid enough, for cutting blocks. The snow up here seemed to have fallen very quietly in light breezes or calms. We could thrust the tent pole (6 feet long) right down without meeting resistance, which showed there was no hard layer of snow."

Small quantities of snow undoubtedly fell on the top of the Plateau at frequent intervals, and Bowers notes that the horizon was rarely clear. This may not be an occurrence common to every year, but it seems possible that the phenomenon is caused by the turbulence of the atmosphere due to the passage of the wind across the surface undulations, causing precipitation in one area and evaporation in another. If this is so, the net gain to the surface may be small.

Scott notes, in 87° 20′ S. lat., that the sky was here overcast for the first time after reaching the Plateau, on the inward journey to the Pole. Haloes are also infrequently noted in the Meteorological Log, except within 3° of the Pole, where mist, fog and falling crystals were constantly recorded.

There seems little doubt that, where the wind was definitely blowing downhill, precipitation was not excessive, possibly even was exceeded by ablation in the summer months. This suggests that a wind circulation, such as that postulated by Hobbs, carries with it conditions which are unfavourable to the continued growth in thickness of such a Plateau, and which set a limit to the admissible slopes. Thus, if Hobbs is correct in his postulate, it seems to us that, wherever the general slope of an elevated dome exceeds a certain value, there ablation should exceed deposition, and there the snow surface should change to a surface of ice. In support of this view, we have the undoubted fact that the surface of large valley glaciers leading from the Plateau are generally free from snow (in summer, at least), and that towards the foot of such a glacier as the Beardmore, when the surface again becomes level, precipitation definitely exceeds ablation, as is the case on the Ross Barrier.

On reviewing all the known data referring to snowfall, ablation and movement of the ice, we must confess that no definite conclusions can be drawn, except that the value of snowfall less ablation is probably greater in the neighbourhood of the Pole than further north towards the head of the Beardmore Glacier, where the value may be negative. Even where the intensity of snowfall is apparently greatest, it seems possible that it may well have been overrated, for the local and temporary wind eddies, due to the inequalities of the snow surface, cause almost permanent formation of fog

* 'The South Pole,' vol. 2, p. 117.

and deposition of snow in some quarter of the horizon. In other quarters ablation may, at the same moment of time have exceeded precipitation. The balance over long periods and considerable areas would then be a very close one.

That the Plateau ice is indeed moving is evident from the pressure ridges which have been observed on all sledge journeys. These are more intense near the heads of the outlet glaciers, and become smaller as their distance from the summit decreases. David states that, on the Magnetic Pole journey, the undulations were still about 50 feet high 70 miles back from the Antarctic Horst, though they died out as the summit of the Plateau was reached. They are therefore clearly connected with the slope of the Plateau.

On the Plateau near the Pole, the slopes were considerably steeper and the undulations apparently larger, measuring here about 5 to 7 miles from crest to crest. Crevasses were very numerous towards the heads of the glaciers, but were observed for the last time on the outward journey by Scott in latitude 86° 15′ S. on the top of one of the undulations. The last crevasse observed by Shackleton was also in about the same latitude. The crevasses seem related usually to the crests of the undulations, but Shackleton suggests they are formed over submerged ridges and peaks and therefore that the land cannot be very far below the ice surface. On this point—the thickness of the ice sheet—we have no direct information whatever. It would be surprising, in our opinion, if the thickness of the ice sheet exceeded 2000 feet at any point away from the head of a glacier, and this figure seems to us an outside estimate.

In Mawson's "The Home of the Blizzard," the suggestion is made that the irregular variations in magnetic declination on the journey over the Plateau towards the Magnetic Pole, may have been due to local attraction from land masses close to the surface of the Plateau. This explanation is no doubt possible, but cannot be accepted as definite evidence of the thinness of the Continental-Ice sheet.

Possibly the most interesting result derived from all the information obtained by various sledge journeys on the Plateau is, that the summit of the Plateau lies in all cases fairly close to the great range of mountains running approximately south, at least from Mount Nansen to the Beardmore Glacier, and continuing thence in a south-easterly direction. If snowfall exceeds ablation on the larger half of the continent, as appears likely, it is difficult to see how the ice-divide could possibly be maintained in such an asymmetrical position as it now occupies, unless the South Victoria Land Horst is still rising.

Either this must be so, or there must be a very much greater outflow of ice on the opposite side of the continent. It is possible that this may be the explanation, for the whole land-mass to the west of the horst appears to slope gently away from the latter. The outflow of the Continental-Ice to the west is severely restricted to the few outlet glaciers such as the Beardmore Glacier, Shackleton and Barne Inlets, the Koettlitz, Ferrar and Mackay Glaciers, etc. Along the margin from Coats Land to Kaiser Wilhelm Land there may be, and probably is, an almost uninterrupted outflow unconfined by rock walls. Such an outflow might dispose of many times more ice without any appreciably greater velocity of movement. Whatever the explanation of the asymmetry of the ice-

divide, it is difficult to escape the conclusion that snowfall and ablation are fairly closely balanced over almost the whole area of the Antarctic Continental-Ice.

As pointed out by Professor David, the land shows indubitable evidence that the surface of the Beardmore Glacier at a recent period stood some 2000 feet higher than at present. This fact certainly indicates that the thickness of the ice sheet on the Plateau was at one time greater, though no conclusions can be drawn as to how much higher the surface stood. It does seem, however, probable that a much more intense glacierisation might be produced by quite a slight increase in snowfall, other factors remaining constant.

Too much emphasis cannot be laid on the fact that, if Hobbs' postulate is correct, there should be a limiting slope and therefore a limiting thickness which a sheet of Continental-Ice of given extent can attain in any given climatic conditions, and that an air circulation such as that postulated by Hobbs is essentially one which demands, where the slopes are sufficiently steep, that ablation shall exceed precipitation. It is also important to note that, even quite close to the Pole, a not inconsiderable portion of many mountains remain free from a permanent snow covering.

It is unfortunate that the results of Mawson's Expedition have not yet been published, as here the Continental-Ice flows down evenly to the sea and the gradients are not very steep. (It is certainly a fact that the surface of this ice sheet at the edge of the continent is, in places at least, formed of ice, as at the Gaussberg.) When the results are available, interesting information should be obtainable as to the relation between surface gradient and probable rate of movement of the sheet.

We have every reason to believe that meteorological conditions on the summit of the Plateau west of the Royal Society Range differ considerably from those which obtain near the South Pole. In the first instance, the temperatures on this portion of the Continental-Ice are certainly low when the sun is low in the south, but there is a great difference between the "day" and "night" temperatures during the 24 hours, sometimes as much as 25° F., due to difference in insolation during the course of the day. The wind force observed by Captain Scott west of the Ferrar Glacier is, however, comparable with that met by him on his journey to the Pole nine years later.

The conditions on this western journey were apparently very similar to those observed by Professor David in his journey to the Magnetic Pole, both Scott and David noting that the wind direction varied, becoming more southerly, as the distance from the coast increased.

A most interesting result appears from a comparison of the conditions recorded by Mawson's parties on the Continental-Ice Sheet with those of all other observers. This lies in the fact that very high wind velocities were reported by all Mawson's parties, even that which visited the Magnetic Pole area and which attained a point very close to that where David turned back. This result is of great interest, and indicates that wind conditions may vary greatly from year to year on the Plateau. The differences, both in wind velocity, temperature and snowfall, between the first and second years at Cape Evans, lend additional force to these observations.

We are thus unable in the general case to draw reliable conclusions regarding the relative snowfall in different portions of the Antarctic from observations made at different places in different years. There seems little doubt, however, that the regions visited by Drygalski and Wild experience a greater snowfall than does the Ross Sea Sector, though we are left in doubt as to whether the wind velocity is greater or less in normal years than in the years of observation.

It is also interesting to note that the soft snow surface which is typical of the Continental-Ice in the neighbourhood of the Pole has not been observed elsewhere, and it is probable that this fact is due partly to greater snowfall and lesser wind velocities near the Pole and partly to the fact that the temperature is here *always* low.

Island-Ice.

As pointed out in the chapter on "Classification of Land-Ice Formations," there is little difference, except that of size, between Island-Ice and Continental-Ice, the former differing from the latter chiefly in the extent of the land surface on which the ice sheet is formed.

In this classification, Shelf-Ice is placed in a class by itself as formed in an area where precipitation, movement and wastage are all active, and where none is preponderant. In the previous section, moreover, an indication has been given that precipitation on the Antarctic Continental-Ice sheet probably exceeds evaporation, that this preponderance is probably less or non-existent on the valley glaciers leading down from the Plateau ice, where the slope is considerable, but is restored or more probably increased on the level Shelf-Ice which floats on the sea.

There is in fact every reason to believe that precipitation is greatest in those regions which border the open sea. On an island, where all winds are winds of high percentage humidity, we should expect an exceptional precipitation in the form of snow, provided the temperature conditions are favourable. Here, within certain limits, the precipitation might be greater the higher the air temperature. It is more than probable, therefore, that the precipitation of snow may be greater on islands north of the Antarctic Continent than on the coast of the continent. If this increased precipitation is not fully compensated by increased ablation, the necessary conditions for the formation of Island-Ice are attained. Thus, the possibility exists that cappings of Island-Ice will be formed (as is indeed the case) on islands far north of the Antarctic Continent, though in some measure, their occurrence may be said to demand a greater excess of precipitation over ablation than is necessary for the formation of any other type of ice-formation.

We cannot speak with authority on this point, and no examples of Island-Ice were visited by our Expedition. Their place in the scheme of the classification should, however, be made clear, as their formation seems to demand the greatest excess of precipitation over ablation of all types. Their occurrence so far north is one reason for the suggestion made that a more intense glacierisation of the Antarctic Continent might ensue, if the temperature conditions were ameliorated.

HIGHLAND-ICE.*

As pointed out in the last chapter, a sheet of Continental-Ice may, if the supply becomes inadequate in comparison with denudation, degenerate into a number of separate Highland-Ice sheets. Examples of this type of ice-formation are very numerous in the Ross Sea sector, being easily distinguished from the preceding types by the fact that the contour of the ice sheet closely follows that of the ground below. Highland-Ice, though common in the Antarctic, has seldom been actually traversed, and our information is therefore far from complete. Probably the best and most easily accessible sheet is that which covers practically the whole of Ross Island and which is surmounted by the active volcano, Erebus. Many excellent photographs showing this formation can be found in the reports of expeditions which have wintered on Ross Island, and an additional one is given in Plate CXXVI.

Ross Island (Map III) is roughly triangular in form, the north side being washed by the waters of the Ross Sea, both in summer and in winter, the south forming a rampart against the thrust of the Barrier and the west side forming the eastern boundary of McMurdo sound, which is frozen in calm winters, but the greater part of which remains open in winters with much windy weather. Owing to its proximity to the open sea, we might expect a heavy snowfall on Ross Island, but there seems no doubt that this is far from being the case, except locally—for example, on the lower slopes facing the Barrier. Here the snowfall is probably exceptionally heavy, and here the average wind velocity is clearly much less than elsewhere on the Island. The observations of three expeditions have shown that the strong winds at sea level are predominantly from the south-east, but at higher levels westerly winds assume greater importance until, a little distance above the summit of Erebus (about 14,000 feet), westerly winds predominate. Owing to the proximity of the open sea and convection therefrom, temperature conditions at the summit can vary comparatively little during the year, but at lower levels, especially during the winter months, there must be a considerable temperature gradient from south to north, which we assume to be the prime cause of the large movement of air from a south-easterly direction. Where the air is forced to ascend, as on the Ross Barrier side of the island, precipitation is naturally very great

* Strictly speaking, Highland-Ice is characteristic not only of an advanced stage in the glacial cycle, but also, in suitable environment, of nearly all stages. The Ross Island Highland-Ice, however, presents unusual features, in that there was probably no deeply-entrenched water-drainage system before the advent of the ice-sheet. The Antarctic Ice-Age must have commenced very soon after the volcanoes (of the Middle Tertiary) raised their heads above sea level, building up upon the subsided Beacon Sandstone the mass of lava and *débris* which now forms the most historical of all Antarctic lands. Though torrents of water must have scoured the slopes after successive eruptions of molten material, the work of water must have been largely confined to such catastrophic periods, if our reading of the sequence of events is correct. Certainly, the eruptions of latter years which have built up the present active crater of fragmentary material seem to have left their *débris* intercalated with ice layers of some thickness in places. This is suggested both by the appearance of lenticular white bands in one or two places, and by the occurrence—noted by Professor David—of rows of steam jets along certain definite lines above lava beds. ('Heart of the Antarctic,' vol. 1.)

but elsewhere falling snow is swept away by the high winds, either when falling, or at a subsequent date. The latter conditions are not favourable to excessive snow precipitation or accumulation. Moreover, apart from the action of the snow-charged wind in chiselling away the surface of the ice sheet, the high average wind velocity notably assists evaporation, even when the air is almost saturated. Add to these the presence of lava outcrops, steep slopes, and wind-blown dust and pebbles on the surface, and all the factors (except high temperature) which favour ablation are present, so that it is in no way surprising to find that snowfall only slightly exceeds ablation on this island.

In the circumstances, it is hardly a matter for comment to find that, where measurements of the glacier movement have been made, this has generally been small. Thus, the rate of movement of the Barne Glacier is only 30 feet per annum, and there is definite evidence that the glacier end is now in process of retreat, though the Highland-Ice still reaches the sea over a large part of Ross Island. Though, moreover, the ice reaches to the sea on by far the greater part of the periphery, it is only locally that it appears to advance into the sea until it floats. There is reason to believe also that the localities where this does occur are exceptionally favoured, either by excessive precipitation or by some other predisposing factor. The photograph shown in Plate CXXVI, which was taken from the summit of Inaccessible Island, shows clearly the type of snow covering.

With the exception of the southern side of the island, where precipitation appears to be most abundant, and other local exceptions to be noted later, it is clear that deposition and ablation are so closely balanced that practically the whole of the land is only lightly snow- or ice-covered, not sufficiently thickly to obscure the main contours of the ground beneath. Generally speaking, there is sufficient excess of precipitation to force the ice to extend to the sea, but not to form a floating extension on it, except locally between Cape Evans and Hut Point, facing McMurdo Sound. At a few places—notably, Cape Crozier, Cape Royds, Cape Barne, Cape Evans and Hut Point—the outflow of ice does not submerge the rocky coast; while at Capes Royds, Barne and Evans the terminal face is obviously retreating. Equally certainly, at those points between Cape Evans and Hut Point where a floating extension is projected into the sea, local conditions favour an excess of precipitation over ablation. The only important extension is, however, that of Glacier Tongue, where the velocity of advance probably reaches 2 feet per day; but even here we believe the tendency to be for this excess of precipitation over ablation to grow smaller. The reasons for the formation and survival of this tongue are discussed later in this chapter.

If the existing tendency to deglacierisation continues sufficiently long, it is probable that the present continuous ice sheet will divide into several portions, separated by ridges from one another. The few glacier tongues which now float on the sea will break back to the land, and those parts of the ice sheet which now just reach the sea will retreat and lay bare the outer portions of the island. It is certain that the deglacierisation of the island will not bring to view pronounced valley glaciers.

The reverse process—an increase in the glacierisation of Ross Island from the present stage—would cause the formation of a floating selvage around the whole island, and probably the formation of a Confluent-Ice Sheet between Cape Evans, Hut Point and the Dellbridge Islands. The fact that such conditions are incompatible with the present position of granite erratics on Cape Royds is of great significance, and argues that the ice sheet moving from the Koettlitz Glacier at the time of its maximum extension was of enormous power in comparison with the sheets of ice then flowing down the slope of Mount Erebus towards McMurdo Sound. The shape of Ross Island is, indeed, such that a truly remarkable precipitation would be required to convert the present Highland-Ice sheet into a sheet of Island-Ice. Long before this could take place, the open water surrounding the island would be replaced by Shelf-Ice from other sources. As pointed out in an earlier section of this chapter, the formation of Island-Ice probably demands a precipitation which can only be reached in an open-water situation very different from that of Ross Island which, owing to the presence of the Ross Barrier to the south and sea ice throughout the greater part of a normal year to the west, practically functions as a part of the South Victoria Land mainland.

Piedmont-Ice.

This ice formation, first described from Alaska, where the Malaspina Piedmont-Ice owes its survival to the presence of a broad shore platform, is typically developed in the South Victoria Land region of the Antarctic Continent, where once again its presence is due to the existence of a suitable environment. Piedmont-Ice sheets can only occur in typical development in certain definite topographical surroundings. Thus it is, much more than many other land-ice formations, dependent on the physiography of the region in which it occurs. This fact is, of course, reflected in its definition, which, as modified to cover Antarctic examples, is as follows :—

> " Sheets of land-ice, of which the original main mass was formed by the coalescence of the ice spreading out from wall-sided or valley glaciers over a comparatively level plain at the base of the mountain slopes down which the glaciers descend."

It is still a moot point to what degree valley glaciers—the most striking of all types of land-ice formation—are capable of scooping out the valleys which they occupy, but it will be generally agreed that they can modify them considerably. To some extent, therefore, this type of land-ice may be said to control, rather than be controlled by, its environment. Similarly, Continental-Ice can be independent of the shape of the base upon which it rests, and Highland Ice, though moulded to the major wrinklings of its pedestal, owes its form more to a particular combination of meteorological conditions than to a similar conjunction of physiographical features. Ice-tongues, certainly, depend entirely, both for form and position, upon their occurrence at sea level. Similarly, Piedmont-Ice depends mainly upon, and is restricted to, certain definite positions,

both by the form of the country undergoing glacierisation and by the particular stage of the glacial cycle represented.

Thus, Piedmont-Ice may occur, given suitable physiographical combinations, at any but the greatest heights on a glacierised land surface. Considered this way, it is the logical outcome of the coalition of two or more masses of Expanded-Foot-Ice wherever suitable temperature and alimentation conditions exist in a mountainous region bordered by a flattish plain. This plain may be elevated as a plateau, may be at or near sea level, or may be below sea level. A continental shelf at a depth of 100 fathoms might be a suitable bed for Piedmont-Ice, which would, however, in that case, in all probability be continued out as a wide floating fringe and merge into Shelf-Ice. The two sheets of Piedmont-Ice closely examined by the present Expedition rest upon plains or shelving slopes which—at any rate at their seaward end—are, for the greater part of their length, some distance below sea level, though isolated projections stand out well above.

Modifications of the normal Piedmont-Ice as defined above may arise through excessive alimentation, when the existence of a floating selvage of greater and greater extent may finally cause the ice sheet to become indistinguishable from Shelf-Ice. On the other hand, diminution of precipitation may bring about the isolation of the Piedmont-Ice from its original feeders, leaving it stranded as a stagnant lobe of ice along a steep foreshore which provides no alimentation whatever. Such an isolated Piedmont-Ice sheet would not normally persist for many years, geologically speaking, but a shifting of the zone of precipitation shorewards, or even the intervention of favourable local air currents, might prolong its life indefinitely, as may be seen from the description of the Butter Point Piedmont-Ice which follows later in this section.

Occurrence.

Few masses of Piedmont-Ice have been described by glaciologists, but it is fortunate that, in the original type sheet (the Malaspina Glacier in Alaska) and the South Victoria land examples (the Wilson and Butter Point Piedmont-Ice), we appear to be dealing with ice-formations built up under the extreme conditions which could give rise to the type. As pointed out in the subsequent section dealing with Ice-Tongues, given suitable physiographic environment (plains abutting against mountains), Piedmont-Ice can grow and persist, either as the result of exceptionally great alimentation in regions only just above the snow line, and even just below it, or, in a region of very low temperature, *in spite of* very small precipitation.

The Malaspina Piedmont-Ice appears to owe its existence to the former conditions, the Wilson Piedmont-Ice to the latter. A similar sequence of events produced the Butter Point Piedmont-Ice, but a further factor must be called in to account for its survival and the measure of growth and movement which it still retains.

In the Antarctic Continent, at any rate in the South Victoria Land region, true Piedmont-Ice is confined entirely to the coastal belt, all other parts of the continent where it might develop being swamped more or less completely by other forms of land ice.

Even here, along a coastline of submergence at the "Antarctic" stage of the glacial cycle, conditions would hardly have been expected to be favourable for the development of this particular type. The ice-formations normal to a young coastline of submergence, at this stage, are the Confluent-Ice sheet, the floating Ice-Tongue, and the Shelf-Ice sheet. The presence of Piedmont-Ice along the coast of South Victoria Land may perhaps be correlated with the presence of down-faulted blocks on the seaward side of the horst, which have afforded the necessary pedestal on which the ice debouching from the ends of the valleys of the horst could spread out and coalesce. Another possibility is, that they occupy the site of a raised shore platform formed during a pause in the depression of the coastline, other signs of which, and of the subsequent elevation necessary to account for its present position, are found further up the coast.

Detailed Description.

Plans of the two Piedmont-Ice sheets—the Wilson and the Butter Point Piedmont-Ice—will be found on p. 158 of Chapter V of this memoir. A somewhat detailed description of each is given here, as they represent widely differing sub-types, the former being typical of, and the latter distinctly aberrant from, the definition given above.

(*a*) *The Wilson Piedmont-Ice.*

The Wilson Piedmont-Ice was traversed by the second Western Geological Party on their return towards winter quarters in 1912. This sheet, one of the best examples known, has a total breadth of about 36 miles, and advances almost everywhere along its breadth into the sea. No Ice-Tongue is, however, formed, the supply of ice and snow being insufficient; and the Piedmont-Ice probably comes to an end in the sea when the ice parts company with the ground. Along the whole breadth of the sheet, except at a few rock outcrops, the Piedmont-Ice reaches the sea and ends in a sheer ice cliff of varying height.

Originally, this Piedmont-Ice sheet was probably formed by the coalescence of several glaciers pouring down from the higher levels and debouching upon a comparatively level plain at the foot of the mountain range fringing the coast. With increasing intensity of glacierisation, the coalescence of the glaciers on this comparatively narrow strip, added to by local snowfall, would completely flood the plain, and, finally, at the height of the ice age, would send forth its quota of floating ice to the great Ross Sea Ice-sheet. As the maximum of the glacial cycle was passed, the glacierisation of this part of the coast would wane until the present stage—where the valley glaciers are hardly recognisable as such, and the whole land surface, except for projecting nunataks, is covered with ice—would be reached.

The present Piedmont-Ice fringes the coast to an average depth of 5 miles, if we measure the depth from the coastline back to a point where the more definite valleys can be recognised as such. The ice sheet almost completely covers the broad gently-sloping shelf along this portion of the coast, except at the southern end of the shelf. Along the strip of coast between Marble Cape and the northern side of New Harbour

(Maps I and VII) the ice ends as a vertical wall averaging about 50 feet in height. It advances until it meets the sea, except where high capes intervene, and from Dunlop Island to Cape Roberts the glacier face forms the coastline with no rock outcrops whatever along the coast. The surface is snow covered, bare ice only showing on the steeper slopes near the coast, but the snow is hard and windswept—quite different from that on Butter Point. The contours of the surface are generally reminiscent of those characteristic of rolling downs, but definite valleys occur where the large glaciers debouch into the Piedmont-Ice. Opposite the two larger glaciers—the Debenham and Wright Glaciers—the Piedmont-Ice is heavily crevassed, and here the surface lies below that on either side. A general idea of the contours is given by the map (Map VII).

The increased movement in front of these glaciers gives rise to a very definite series of crevasses. These crevasses are obviously of two types :—

(1) At right angles to the direction of movement caused by movement of the ice over positions where the slope suddenly increased.

(2) At an angle of about 45° to the direction of movement, due to the fact that the central portion of the sheet was moving faster than the ice on either side.

The rate of movement opposite Dunlop Island is clearly slower than in many other parts, yet in 1911 the sea ice in the narrow strait had been subjected to heavy pressure as a result of the forward movement of the Piedmont-Ice during the preceding winter and spring. Debenham expresses the opinion (which he bases on the amount of pressure in comparison with that observed opposite glaciers whose rate of advance is known) that the movement of the ice opposite Dunlop Island is probably 10 to 20 inches per day in summer.

Little evidence is available as to past conditions in this particular place, as the mountains at the back of the Piedmont-Ice could not be visited. The only nunatak of any size lay behind Cape Dunlop, and, from its form, it is clear that the ice once stood here at least 200 feet higher than it stands at present. It seems certain that, at the maximum of the glacial cycle, the movement must have been very considerable and the Piedmont-Ice must have given rise to a considerable body of floating ice.

In conclusion, it is necessary to lay emphasis on the fact that the formation of this Piedmont-Ice sheet is due to the gently-sloping shelf which borders the coast between New Harbour and Granite Harbour. Further north, between Granite Harbour and the Drygalski Ice-Tongue, similar conditions obtain and a similar Piedmont-Ice sheet is formed.

(*b*) *Butter Point.*

As may be seen from a glance at the map of the McMurdo Sound region, Butter Point consists of a mass of ice lying between Blue Glacier and the Ferrar Glacier on the west side of the Sound. On the southern side it is continuous with the Blue Glacier, but on the northern side a gap exists between it and the Ferrar Glacier. It is thus surrounded by water, or sea ice, on two sides and by the ice of the Blue Glacier on the

third. The Piedmont-Ice itself slopes gently up on the eastern and northern sides from a height a few feet above sea level to 1000 feet, where it abuts the land on the western side. The total area is about 25 square miles.

At the south-eastern corner of Butter Point are found the curious moraine remnants known as the "Stranded Moraines"*—an ice mass covered with morainic material derived from the Koettlitz Glacier, which is evidently a remnant of the Koettlitz lateral moraine, the ice beneath being protected from melting by the thick covering of rock and sand. At this point Butter Point is evidently aground, as is clear from the fact that small icebergs derived from the Blue Glacier remain motionless off the face of the glacier for considerable periods. Soundings and observed heights of the seaward face some distance north of the stranded moraines indicate that Butter Point is here afloat.

At present, the Piedmont-Ice has no other important source of supply than that due to snowfall on its surface. (Possibly growth may take place from below, but this seems very unlikely.) In earlier times, it probably received ice from the Koettlitz, the Blue and the Ferrar Glaciers, and from Highland-Ice sheets on the hills between them, while it may also have been notably increased in area by the incorporation of sheets of sea ice laden with snow.

Whatever may have been its origin, however, its presence in the situation it occupies at the present day can only be due to a comparatively heavy excess of precipitation over ablation, a state of affairs to which it is somewhat difficult to assign a cause, in view of the entirely different conditions which hold sway both to the north in Dry Valley and to the south on the foothills fringing the western bank of the Koettlitz Glacier.† Such a change in the conditions affecting precipitation and ablation is, however, not uncommon in the Ross Sea sector. The surface of Butter Point consists of soft snow which has evidently fallen in a comparatively windless area, as sastrugi are seldom pronounced. The surface approximates, in fact, in many ways, to portions of the Ross Barrier, and differs entirely from the ice of the Blue Glacier and the Koettlitz Glacier, and also, as just stated, from that of its neighbour, the Wilson Piedmont-Ice, to the north.

To what cause then must we attribute the local excess of precipitation over ablation, which has led to the revival of the Butter Point Piedmont-Ice ? It is, we believe, due to a modification of the main McMurdo Sound air circulation. The prevailing strong winds further to the east are the south-easterly winds off the Ross Barrier. Opposite the Koettlitz Glacier, these winds are usually deflected to the westward by the draught down the valley from the Plateau. Down the Blue Glacier again, yet another stream of air comes in from almost due west. The combined result of these winds is to shoulder off the lower layers of the main south-easterly blizzards from the neighbourhood of Butter Point. Immediately west of the Piedmont-Ice is a high rock bluff down which no wind comes, but to the north, once again, the westerly winds from the Ferrar Glacier

* The "eskers" of the Memoir on Physiography by Griffith Taylor.

† The excess of precipitation over ablation on Butter Point, between 1908 and 1911 (slightly over two years), was 2½ feet of snow.

assist to form a veritable air cushion, causing a calm area in the immediate neighbourhood of the Point. Meanwhile, it is probable that, at a height above that of the Butter Point foothills, the main circulation is able to drive straight forward across the top of the calm area and thus cause an up-draught of the air over the Piedmont-Ice. The outcome of this combination of factors would be greater local precipitation, especially to the north of the piedmont, and less ablation, the result of such conditions being the adequate nourishment of the Piedmont-Ice, although its original source of alimentation —the outflow from the Continental-Ice and local Highland-Ice—has long ceased to function.

This sheet of ice is thus an excellent example of a " secondary " Piedmont-Ice, the greater portion of the present mass of which has no connection whatever with the original source of the true Piedmont-Ice which was its ancestor. It is in fact a " pseudomorph " after a true sheet of Piedmont-Ice.

With the exception of the little ice at its southern extremity, which marks the maximum extension of the Blue Glacier, all the main mass of the Point is derived from the snow which has fallen upon its surface in past years. Its movement, likewise, which appears to be sufficient to push portions of it sufficiently far forward to float in the sea (though not sufficiently far to develop elasticity enough to eliminate the tide-crack between it and the sea ice) is derived entirely from the flattening-out movement which is due to its own weight. If comparative sections were made through the Butter Point and Wilson Piedmont respectively—avoiding the positions on the latter where its feeders come in—distinctly different outlines would be seen.

Effect of Greater Glacierisation.

It is quite clear that, with increasing alimentation, especially with a decisively greater quota from the feeding glaciers, the Piedmont-Ice sheets of South Victoria Land would swell to form considerable sheets of Shelf-Ice. The first step consequent upon an increase of alimentation would doubtless be the reversal of the last stage in the recent deglacierisation of the region. The Wilson and Butter Point Piedmont-Ice sheets would be joined in one by a floating extension of the Ferrar and Taylor Glaciers.* These, again, would join up with other notable glaciers, Piedmont-Ice sheets, and Confluent-Ice sheets along the coast. There seems no reason to doubt that, at the maximum stage of the last glacial period, the whole of these coastal formations reached out to join with a much more vigorous ancestor of the Ross Barrier, forming a continuous sheet filling the southern portion of the Ross Sea and extending far to the north.

Confluent-Ice.

Less detailed notice is required of the fourth type of ice characteristic of the Zone of Predominant Wastage. Confluent-Ice is essentially a product of the " Antarctic "

* Even to-day a tongue of ice from the Ferrar Glacier abuts against the north-west corner of the Piedmont-Ice. Owing to an oversight this is not shown in the diagram on page 158, but it can be seen in Map VII.

stage of the glacial cycle on a juvenile shoreline of submergence. As such it has a very restricted range, though it is likely to be typically developed in South Victoria Land, which fulfils both the essential conditions for its formation on a large scale.* One of the characteristics of the young stage of a shoreline of submergence is the presence of numerous islands off the coast. The characteristic of the shore phase of the "Antarctic" stage of the glacial cycle is the presence of floating land ice, but in sufficiently small amount to permit the easy definition of certain main types due to quite different causes. A waning of the glacial cycle would do away with floating land ice altogether; a marked increase in alimentation would merge the sheets into one complete girdle covered deeply with snow, and with its original features, due to the presence of a large proportion of ice from the inland ice sheets, largely or entirely obliterated.

Confluent-Ice, as defined in our classification, is :—

> "An ice sheet formed by the coalescence of the floating terminations of several glaciers, but given a definite form and trend by the presence of a land-bar along its seaward edge."

The term is therefore much restricted in application, and is correspondingly unimportant in comparison with those which have preceded it. It has, however, points not common to any other type and it has a distinct physiographic importance, in that it, more than most other types, is likely to lead to reversals of drainage lines as a result of increased alimentation, and is also likely to have a peculiarly efficient scouring action upon the rock islands or peninsulas which form its seaward boundary.

The Campbell-Priestley-Corner Confluent-Ice sheet.

The only sheet of Confluent-Ice examined in detail by the present Expedition is that occupying the north-west end of Terra Nova Bay, the surface of which is shown in Plate CXXII, Chapter V. Here the Campbell and Priestley Glaciers, with many smaller tributaries, pour a big volume of ice into the sea, and this ice is prevented from moving eastward by the rock-bar pier formed by the islands known as the Northern Foothills and Inexpressible Island.† The pent-up stream of ice surges along the fjord thus formed, and, just before reaching the Drygalski Glacier, receives a mighty tributary from the Reeves Glacier to the south of Mount Nansen. There is not wanting the usual evidence to show that, in former times, the ice-flood was at least several hundred feet thicker. A little island—Vegetation Island—lying approximately parallel to the main ice-flow lines, has been glaciated over its summit. Erratics of origin foreign to the district are found high up wherever the containing rock slopes are scaleable. Everywhere, the ice surface was originally at least 300 feet higher, and very likely much more. Along the eastern edge of the Confluent-Ice, the pressure of the ice against the containing rock wall,

* J. M. Wordie, in a Paper before the Royal Geographical Society, has referred to the occurrence of typical Confluent-Ice in Spitzbergen. Here deglacierisation appears to have proceeded somewhat further than in the South Victoria Land sector of the Antarctic. ('Geog. Journ.,' vol. 58, No. 1, July, 1921.)

† Map XIV.

combined with an excess of deposition in the lee provided by the cliffs, causes a distinct bulge which is very characteristic. Elsewhere, the surface is level without marked irregularities, and this is compatible with the supposition that the ice is afloat for some considerable distance back from its edge, perhaps very nearly to the Priestley Glacier, where, however, are the first clear signs, in the form of regular crevasses, of a submerged rock-bar which must be comparable to the " Riegels " of the Dry Valley and the Ferrar Glacier.

Indeed, in many ways, the greatest interest of the region lies in its close resemblance to what McMurdo Sound must have been many hundreds of years ago, before the recession of the ice. This idea will be mentioned again in the Physiographical chapter dealing with this district.

While, in the main, the surface of the Confluent-Ice is flat and in conformity with the hypothesis that it is afloat, there are two series of minor irregularities which are sufficiently pronounced to be worthy of mention. The most marked of these are the quite pronounced waves, barranças, and stream channels at the entrance to the Priestley and Corner Glaciers, which are the result of thaw, radiation from the rocks, and ablation, modifying the original pressure rolls due to the advancing glacier (Plate CXXVII). Less marked, but far more dangerous and troublesome, were the complicated crevasse systems which occurred where the greater glaciers emptied their quota of ice into the less quickly moving Confluent-Ice. The place of junction of the ice from the Campbell Glacier with the main ice sheet was particularly impressive to the sledge traveller.

Owing to the fact that this junction occurred at a place where deposition exceeded ablation in a marked degree, not a sign of a crevasse was to be seen, for they were all adequately snow-bridged, and even the bridges were covered with a uniform deposit of soft summer snow. Underneath this apparently level surface, however, was a veritable network of crevasses of all sizes up to specimens a dozen or more feet broad, and so numerous that it was only with the greatest difficulty that a sound spot could be found large enough to take the tent.

Characteristic of the Confluent-Ice at this spot are the long " railroad " moraines (Plate CXXXVIII, Chapter VII), which stretch out from the Priestley and Corner Glaciers, and which afford a valuable indication of the present state of alimentation of the ice sheet.

Opposite the *massif* between the Corner and Campbell Glaciers, they disappear entirely beneath fresh ice, evidently derived from the increased snowfall in the lee of the rock cliffs. Once submerged, they remain hidden until many miles beyond, reappearing opposite the southern end of Inexpressible Island. The whole of the Confluent-Ice south of Vegetation Island is swept continuously throughout the winter by the strong dry gales from the Reeves Glacier, which are the principal feature of the air circulation of the region. The result of this is ablation on a scale not equalled in any other region which the writers have visited. The whole of the thick layer of ice which has accumulated higher up the glacier disappears, and the moraines once more come to light just before they arrive at the seaward edge of the Confluent-Ice.

In the classification in Chapter V we have placed the Ice-Tongue second in order of the Ice-Formations of the "Zone of Predominant Wastage." If, as in the Arctic and Antarctic at the present day, a sheet of Continental-Ice, or even, exceptionally, of Island-Ice, radiates outwards from a central land mass, through the medium of valley or wall-sided glaciers, to the sea, one of three things will happen. It may be that, as in the North Polar regions, and particularly Greenland, conditions will be such that the various denuding forces will be able to keep all the advancing glaciers cut back to tide-level. It may be, as in both Polar regions, that when circumstances, such as a gradually shelving shore, favour them, many glaciers may push their way out to sea to a considerable distance, forming a fringe of "stranded" or "fast" land ice along the coast (the Piedmont-Ice). It may be, again, as in the Antarctic, that certain of the most favoured —not necessarily, it would appear, the most vigorous—of the glaciers will make their way still further out to sea, quite irrespective of the presence or absence of a friendly shore platform on which they might rest, until they float in the sea water as immense ice-pontoons—the floating Ice-Tongues so characteristic of the Antarctic littoral.

Perhaps the greatest of all the Ice-Tongues which have yet been discovered and partially explored is that of the Denman Glacier, pushing through the Shackleton Shelf-Ice with an accompaniment of pressure waves, blocks and chasms so chaotic as to be impassable to sledge parties.* Better known, however, and occurring in the region explored by the present Expedition, are the Dugdale Ice-Tongue (lat. 71° 30′ S.), the Drygalski Ice-Tongue (lat. 75° 15′ S.), the Nordenskjöld Ice-Tongue (lat. 76° 10′ S.), the Mackay Ice-Tongue (lat. 77° S.), and the Erebus Bay Ice-Tongue (Glacier Tongue) (lat. 78° 40′ S.), along the coast of South Victoria Land.†

At once the question arises: What are the essential conditions for the survival of masses of land ice, often of great extent, many miles (sometimes hundreds of miles) long, in such apparently equivocal positions, swept by the winds of the comparatively warm shore zone, buffeted by the waves, and often strained by strong ocean currents sweeping along shore at right angles to their length? To what do they owe the undoubtedly considerable measure of persistence which they enjoy? Why is it that the Greenland glaciers, for instance, some of which have a movement certainly exceeding that of the swiftest known Antarctic glaciers, do not have floating extensions of appreciable length? Are the Antarctic Ice-Tongues to be regarded as survivals from a previous age of greater glacierisation, or are they to be accounted for by present conditions? All these questions and others have intrigued the glaciologists of the different expeditions, as well as many other scientists who have never set foot in the Antarctic, but whose power of absorbing and correlating facts discovered and recorded by others renders their contributions to Antarctic Glaciology of outstanding importance.

* The map of the Shackleton Shelf-Ice and the Denman Glacier, published in the 'Home of the Blizzard,' rather makes one doubt if the Ice-Tongue protruding from the former really belongs to the latter glacier.

† Map I.

Only in one case has direct measurement of the velocity of an Antarctic Ice-Tongue been made. Measurement with a theodolite showed the movement of the Mackay Ice-Tongue during the summer of 1911–12 to be at the rate of 2·8 feet per day. During the remainder of the year, there can be little doubt that movement is considerably less.

Measurements of the movement of Greenland glaciers during the same period of the year give considerably greater velocities.* It is therefore to facts other than, or rather additional to, the rate of advance of the present valley glaciers that we must probably attribute the persistence of the Antarctic Ice-Tongues. This conclusion is also borne out by a consideration of different Antarctic glaciers. The persistence of Glacier Tongue, for instance, is in marked contrast to the breaking back of other glaciers along the South Victoria Land Coast which, judging from a comparison of alimentation areas and local precipitation, should be better nourished, but which occur in less favourable positions. The question then arises: What factors likely to influence the duration of survival of floating ice masses, either favourably or the reverse, differ appreciably in Greenland and the Antarctic?

Many hundreds of glaciers, both in the Arctic and the Antarctic, reach sea-level and front the sea as vertical cliffs, but only comparatively few—and these almost without exception in the Antarctic—manage to push their way seaward sufficiently far for their ends to leave the ground altogether. If we examine the factors which influence the seaward end of such glaciers, we recognise certain agents tending to break off, or otherwise remove, the ice which is exposed to their assaults. Such agents, peculiar to the glaciers reaching the sea, are the tides, the waves, the temperature of the sea water and sea currents. Other agents not confined in their action to such ice-formations, but nevertheless entering into the problem to a marked degree, are winds and the temperature of the air. Yet other factors which are likely to affect, and undoubtedly do affect, the persistence of Ice-Tongues, are their position in sheltered or exposed portions of the coastline, and the angle at which the feeding glacier descends from its névéfield. We thus have to consider the effect of at least eight factors, besides rate of movement:—

(*a*) Position.
(*b*) Tides.
(*c*) Currents.
(*d*) Winds.
(*e*) Waves.
(*f*) Slope of Glacier.
(*g*) Aerial Temperature.
(*h*) Marine Temperature.

If we apply the test of the above factors to the two type-areas mentioned—Antarctica with, and Greenland without, Ice-Tongues—we shall at once be able to rule out several as being either common to both areas in like degree, or as not being of vital importance.

* Chamberlin and Salisbury, 'Geology Textbook,' record that some of the glaciers of Greenland are moving in the summer 50, 60, or even more, feet a day. A measurement as high as 100 feet a day has been made, but this was a special case of ice crowding into a narrow channel.

Tides are of similar magnitude in the Arctic and the Antarctic. At any rate there is, we think, not sufficient difference to cause a definite divergence in the degree of persistence of seaborne land ice. Winds and waves, also, may be ruled out of court in this connection, because what action they do have must act in a direction tending to bring about results exactly opposite to those known to exist. There is no doubt that both wind and sea are more boisterous around the coasts of Antarctica than of Greenland, and yet it is round the shores of the former that the floating Ice-Tongue exists in most perfect development. Evidently, the denuding action of both factors must be more than counterbalanced by some other more potent agency. Shelter and slope again can be ignored, since, although undoubtedly glaciers favourably situated and reaching the shoreline at a low angle do tend more to extend seaward as Ice-Tongues, yet favourably situated glaciers do exist along the Greenland coast without producing seaward extensions. Also, Antarctic glaciers meeting the sea at a steeper angle than the majority of large Arctic glaciers, do persist seaward as Ice-Tongues—for example, " Glacier Tongue," in Erebus Bay of McMurdo Sound.

By the process of elimination, then, the factors which might be primarily responsible for the survival or destruction of Ice-Tongues have been reduced to three:—

(*a*) The presence or absence of strong currents.
(*b*) Aerial temperature, especially in summer.
(*c*) The temperature of the sea.

All three of these differ from the factors already passed in review, in that they are markedly different in the two regions under consideration, and in that their action would, as it happens, naturally tend to bring about the result which does actually exist in Nature.

With the exception of Ice-Tongues formed at the head of deep bays or other indentations of the coast, one of the characteristics of these land-ice formations is, that they will extend out as piers, practically at right angles to the coast, in a position where any long-shore current is likely to have maximum effect upon them. The pressure of such a current upon an Ice-Tongue must be immense, as can be gauged by the swirl of the water past its end, and as is also indicated by the stripping off of the upper layers of water, which frequently takes place, leading to the upraising of the lower layers in lee of the tongue. This action is well shown by the persistence of open-water pools in this position, sometimes throughout the winter. Such currents exist both in the Arctic and the Antarctic, but are certainly much stronger along Arctic shores, owing to the comparatively circumscribed nature of the few outlets from the North Polar Basin. So far, then, the swift longshore currents might be an important factor in bringing about the suppression of floating terminations to Arctic glaciers.

The persistence of Antarctic Ice-Tongues right across quite strong currents, however, seems in itself sufficient to prevent this factor from being considered in any way dominant. If currents had any great mechanical effect, such elongated pontoons as Glacier Tongue and the Nordenskjöld Ice-Tongue could not exist. The solvent effect of the sea water

in longshore currents must undoubtedly be great, but this action is intimately bound up with the remaining two agencies which will now be considered together :—

Air and Sea Temperature as affecting Ice-Tongues.

Undoubtedly, the most marked contrast between the conditions affecting Arctic and Antarctic glaciers at sea level is that caused by the difference in the summer temperature of the two regions. In the winter, conditions approximate much more closely ; but, in the summer, as evidenced particularly by the difference between the Arctic and Antarctic flora, a temperature contrast exists, comparable in its effects with that between cold and warm temperate climates. The difference as expressed in degrees is not great, but it is all-important just because it lies near the temperature of the freezing-point of water. The mean Arctic summer air temperature is above, the Antarctic below, 0° C. A similar difference, though much smaller when expressed in degrees Centigrade, must exist between the summer temperatures of Arctic and Antarctic sea water. Even a difference of a hundredth of a degree in the temperature of Arctic and Antarctic surface sea layers must react with immense effect on the persistence or otherwise of the ice below sea level.*

Here, at last, we seem to have a factor adequate in itself to explain the fact that, in the Antarctic, Ice-Tongues exist, and, in the Arctic, the glaciers in the main do not extend far beyond tide level.

As is shown in the chapter on Icebergs, by far the most potent factor in the formation of bergs of true glacier ice (glacier icebergs) is the under-cutting action of sea water, which is of course especially active in summer. Almost everywhere where ice is afloat in the Antarctic—certainly wherever a current circulates under the ice—the present sea temperature conditions are such as to permit a net loss from beneath during the year.

This loss is naturally more rapid in summer and near the edges of the ice sheet. It, combined with the rate of movement of the glaciers nourishing the floating ice sheets, sets the seaward limit, which will change with a change in either of the two factors concerned. Given constant glacier movement, a rise in the mean temperature of the sea would cause a recession of the Antarctic Ice-Tongues ; a fall would cause an extension. A very small rise in the summer temperature of the Antarctic sea would, in the opinion of the writers, reduce the shore-girdle to the semblance of Greenland of the present day, without the intervention of any other factor. If the Greenland shore currents are, as appears to be probable, more rapid than those along the Antarctic coastline, the necessary rise in Antarctic temperature to bring about this result would be rather less. That this rise is actually taking place appears quite likely, from the changes recorded off South Victoria Land within Antarctic historical times. It might well be a more potent factor in bringing about a marked degree of diminution of the floating-ice extensions than any starvation due to changes in the " glacial anticyclone."

The single exception to the rule that Antarctic glaciers alone have floating extensions appears to be provided by certain Alaskan glaciers, in which country also occurs the

* Salinity of sea water is no less important than sea temperature.

typical sheet of Piedmont-Ice, the Malaspina Glacier. In his account of the results of the Harriman Alaskan Expedition, Gilbert* expresses the opinion that the Turner Glacier, which fronts the sea as a cliff and has no surface gradient towards its seaward termination, is afloat. If this is so, it is a further testimony to the way in which analogous results may be brought about by excessive precipitation and by low temperature, respectively. Alaskan glacierisation is the expression of one extreme, Antarctic glacierisation of the other. In Alaska, a local excess of humidity in the air, with sufficiently low temperature to ensure its precipitation as snow throughout the greater part of the year on the highlands, has brought about many of the same forms of land ice as have been produced under the desert frigid conditions of the Antarctic Continent of the present day. In the former case, occasional floating extensions of glaciers exist *in spite of* the relatively high sea and air temperature; in the latter, they persist *because of* the low sea and air temperature. We have here the two extreme sets of conditions, and between these may occur an infinite number of combinations of precipitation with temperature which may produce similar results.

All other glacierised regions of the present day apparently lie outside the limits represented by these two extremes.

Characteristic Features of Ice-Tongues.

Shape.—One typical shape of comparatively slow-moving Ice-Tongues, in plan and section, is shown in Figs. 72 and 73 of Chapter V. Other Ice-Tongues are shown in Maps I, IV and VI. It is not probable that any Ice-Tongues have shapes essentially different in section from that shown, the characteristic of which is the so-called "ice apron," where the original thickness of the parent glacier is rapidly reduced to the normal thickness of floating land ice under present Antarctic conditions. The main agencies bringing about this decrease in thickness are two in number:—

(1) The natural flattening due to gravity which takes place after the release of the ice stream from the confining walls of its valley, and

(2) The melting action of the sea water upon the bottom layers of the ice.

The triangular shape of the typical Ice-Tongue must be attributed in the main to icebergs calving from either side as the ice moves forward. The influence of the sea water upon the mass will naturally be greatest at the edges, and this will be shown by the constant under-cutting and consequent calving of bergs. Along the Victoria Land coast of the Ross Sea, a distortion effect might be expected through the presence of a current from south to north, bringing an ever fresh volume of surface-warmed water in the warmer months of the year to attack the southern face of the tongues.

This influence is, however, counteracted in at least two ways. The prevalent southerly winds tend to trap pack and bergs against the south side of the tongues, and thus much of the energy stored up in the water of the current is wasted upon these adventitious masses of ice. Also the stripping off of the upper layers of water in passing

* G. K. Gilbert, 'Report of the Harriman Alaskan Expedition.'

under the tongues, causes the upward flow on their northern sides of the relatively saline waters from the middle depths. In the summer, the solvent action of these lower layers might not equal that of the surface waters, but, on the other hand, their action continues without much diminution throughout the year. Iceberg separation in winter is also favoured along the northern edge of the tongues by the presence of the winter waterholes referred to in Chapter X. The net result of the three factors appears to be the production of fairly symmetrical tongues, except in certain special cases referred to later.

It is to be noted that the calving of the icebergs does not normally take place along pre-existing lines of weakness such as crevasses. If this were the case, an entirely different and much more irregular shape would result. In the cases where glaciers reaching sea level are very much broken up, owing to unevenness or pronounced sudden change of level in the last portion of their course, the ice calves off in strips parallel to the coast as it begins to float and the annual increment is thus carried away as icebergs.

Cases have been reported of fleets of bergs, collected during the winter in front of such advancing glaciers and merely awaiting the break up of the sea ice to allow them to move off. Such occurrences are proof positive that the slope where a glacier reaches sea level is of distinct importance, though often overshadowed by other factors. It is quite clear that a glacier reaching the sea at a high angle and with a strong horizontal movement will split from the bottom upwards, and this split will occur at a position where no further change of slope can occur to promote recementation. Sudden changes of slope further up the glacier valley, even changes so great and so numerous as to cause a succession of ice falls, have often little or no effect upon the behaviour of the ice on reaching sea level.

Ice from such a glacier, providing that it goes to sea with a final gentle slope, will often be so thoroughly recemented as to cause the former crevasses either to be closed completely or converted into dykes of more or less pure blue ice. Under such circumstances, the cracks may become positive sources of strength, binding together ice which would otherwise fracture more easily than it does. It requires very little time to cause this recementation in some cases, and this is particularly seen in such cases as Glacier Tongue and Warning Glacier. The latter is figured in Plate CXXVIII. The steep slope just before reaching the sea is well seen. Yet, in the face of the cliff, the deeper of the old crevasses mainly show as very perfect ice-dykes.

This case is probably an exaggerated one, for the conditions under which the glacier exists are such as to favour an unusual amount of thaw in summer. It is exposed to the northern sun, and it is surrounded by black rock peculiarly favourable to the production of water through insolation. Nevertheless, such examples of rapid conversion of crevasses from lines of weakness into girders of strength are not uncommon in the Antarctic, and it is significant that these vertical ice-dykes do not form the boundaries of Ice-Tongues. Rather, they may be seen cutting its seaward cliff at any angle, showing clearly that the latter is sculptured quite irrespective of their occurrence.

Undoubtedly, however, occasional breaks along lines of weakness do take place in Ice-Tongues, though certainly less commonly than in Shelf-Ice. Such a cause must probably be assigned to the breaking away of Glacier Tongue in March or April, 1911. Lines of weakness which are likely to produce similar breaks on a large scale may be observed in the plan of the Nordenskjöld Ice-Tongue shown in David and Priestley's illustration in the Shackleton Memoir.

While the triangular shape would appear to be the natural form assumed by an Ice-Tongue pushing its way steadily outwards from the coast in spite of submarine denudation, other types do occur which are deserving of notice.

One of the most surprising features of the Antarctic coastline is the long pontoon-like, approximately parallel-sided Ice-Tongues, good examples of which are seen in Glacier-Tongue, Mackay Ice-Tongue and the Nordenskjöld Ice-Tongue.* In such cases, the length of the tongue appears to be altogether disproportionate to its breadth, and its apparent fragility is such that there has always been a temptation to call in submerged islands or shoals to account for its persistence. Nevertheless, evidence has gradually been accumulating—especially in the case of Glacier Tongue—in favour of the theory that, except at its shoreward end, such a tongue need have no support other than the water upon which it floats. Exhaustive soundings round Glacier-Tongue have failed to discover any shoals†; the contour of the tongue is such as to render the observer certain that no island, similar to, but of less elevation than, the neighbouring Dellbridge and Dailey Islets affords any great measure of support beneath it. For a long time the tongue was looked upon as a relic of the former ice-sheets which must have filled McMurdo Sound at no geologically distant date. The researches of the present Expedition have, however, shown that it is in comparatively rapid movement, and the writers' opinion is that the present supply of ice is quite sufficient to account for its existence.

We have, therefore, in this and in other similar cases, to account for the variation of the tongue from what we believe to be the normal form. Why is it that submarine denudation has not "sharpened" the edge of these particular tongues? In the experience of this particular Expedition three such cases were met—the Nordenskjöld, the Mackay, and Glacier Tongue.

Is there any factor common to all three which might account for their shape? At least two factors may be cited which would both tend to work in this direction, and both of these take effect in the case of Glacier Tongue, and probably in the case of the others also:—

(*a*) An examination of Glacier Tongue shows that, while the surface of the tongue is of ice, the sides of it are filled with snow-drifts, stretching up often from the sea ice below to the top of the tongue (Plate CXXIX); elsewhere curling over as great and fantastic cornices which, however, do not everywhere meet the drifts rising from the sea ice. The cause of this local accumulation of snow—which, from the very fact that many of the drifts are based upon sea ice, must largely be annual—is undoubtedly a

* Map I. † A sounding of 224 fathoms was obtained at the end of the tongue in January, 1911.

peculiarity of the air circulation in this portion of McMurdo Sound. Sledge parties containing one or more men interested in Meteorology have again and again remarked that, just in the latitude of Glacier Tongue, they have walked out of northerly airs they had carried with them from Cape Evans or Cape Royds into the normal southerly breezes.

Often this change has been marked by the occurrence of quickly forming, but not always quickly vanishing, whirlwinds of fresh-formed snow. Local overcast weather caused by a mist of crystals has also been observed. There appears to be no doubt that Glacier Tongue happens to lie just at one of those junctions where a local air circulation meets the off-Barrier airs. Hence, excessive precipitation takes place in this particular region, and this, in its turn, is the cause both of the unusually heavy snow covering on the sea ice in the immediate neighbourhood of the tongue (compared with that to the north and south) and also of the snow-drifts which line the tongue on either side. It is not contended that the local precipitation has any dominant effect upon the persistence of the tongue. That cannot well be so, for the southerly gales keep the upper surface windswept and polished except in hollows. It may, however, be responsible in some measure for the persistence of its sides as parallel, rather than converging, lines. Snow-drift and snow cornices always form an appreciable portion of its seaward edge on either side. Probably the sea ice in some of the small bays and coves which occur along its length is trapped, and with its superincumbent layer of snow is added temporarily to the body of the Tongue. Such lateral accumulations must have at least some effect in lessening the action of the sea upon it.

(*b*) While this interesting process may have some effect in modifying the shape of Glacier Tongue, it is believed that the second factor, now to be cited, is the really important one which acts in all similar cases. Measurements of the velocity of movement of Ice-Tongues and the glaciers which supply them are unfortunately not common. Movement which is probably much faster than that of the majority of the glaciers has, however, been proved for two of the ice streams under consideration—the Mackay Ice-Tongue and Glacier Tongue.

We believe the Ice-Tongues which extend furthest out to sea must usually be those which move forward fastest, but that the time taken for a given mass of ice at the shoreward end to reach the terminal face is less in the case of the longest than in the case of the shortest Ice-Tongues. As a consequence, we would expect the most quickly moving tongues to approximate to the shape of a truncated cone, while the more slowly moving tongues would approximate to a more perfect conical form.

It is believed that other more normal tongues—such, for instance, as the Warning Glacier Ice-Tongue, and the Dugdale Ice-Tongue—are not moving nearly so fast. The Drygalski Ice-Tongue, also, though evidence of movement comparable to that of the Mackay Ice-Tongue has been cited by David and Priestley, is so long that it must have taken an appreciably longer time for ice to travel from its shoreward to its seaward end than in the case of the two Ice-Tongues cited above. If the denudation of an Ice-Tongue takes place, as we believe, mainly by undercutting by the sea, it stands to reason that the amount remaining on the sides of the tongue will vary according to the speed with which

it moves forward, other things being equal. If the movement of a tongue is fast, it will lose less from its sides before it reaches a given distance from the shore. Thus, of two tongues of similar length, the one moving fastest will be most likely to assume the pontoon form. No evidence is directly available for the Nordenskjöld Ice-Tongue, but the Mackay Ice-Tongue and Glacier Ice-Tongue are known to move unusually quickly, and it is probable that they owe their shape in the main to this fact.

Yet another peculiar shape of a tongue is that which occurs in the Dugdale Glacier. Here the breaking back of the tongue, even since 1899, appears to have resulted in the conversion of a double tongue into a triple tongue (Fig. 74, Chapter V).*

It is possible that this breaking back will soon result in, firstly, separation into two tongues, and, secondly, the final elimination of the floating terminations of the Murray and Dugdale Glaciers, which lie in a corner where deglacierisation is unusually far advanced. It might be expected that, in a composite Ice-Tongue whose component glaciers quite likely—indeed, almost certainly—move at different speeds, lines of weakness would develop in the same way as, though in less degree than, they do where strongly nourished glaciers advance through comparatively stagnant Shelf-Ice or Piedmont-Ice.

Bounding Walls of Ice-Tongues.

(*a*) *Verticality of the Wall.*

The Ice-Tongue is bounded on all its seaward sides by vertical cliff walls, the perpendicularity of which is due entirely to the undermining action of the sea and subsequent calving. While there must be a slightly greater movement of the upper layers than of the lower, this can only be extremely slight, certainly not sufficient to bring about any appreciable effect before the adjustment due to calving has once again produced exact verticality. Such modifications as do occur are due to accretionary or erosive agencies. The addition of snow as a pronounced snow cornice frequently gives an overhang to portions of a lee cliff; the breaking away of the upper portions of only partially recemented seracs sometimes has the opposite effect, and may give rise to marked leaning pinnacles (Plate CLXXII, Chapter VII).

The straight up-and-down contour of the cliff may also be considerably modified in the short summer season by flutings due to thaw, which gives rise sometimes to quite picturesque effects (Plate CLXXXVII, Chapter VIII.)

In the early autumn, similar effects may be produced by the spray from heavy seas: in the late autumn, the same agency may give rise to unsightly bosses which, combined with under-cutting near sea level, may give the cliff quite a pronounced overhang.

(*b*) *Height of the Wall.*

In height, known Ice-Tongues vary from a few feet, as in the lower portions of Glacier Tongue, to 150 feet. The cliffs of some Ice-Tongues present a singularly uniform appearance for miles, differing very little in height throughout the greater part of their

* The Ninnis Ice-Tongue, discovered by the Mawson Expedition off the coast of Adelie Land, has a most extraordinary shape, which only appears explicable on the assumption of the presence of submarine obstacles and holding ground.

length. In other cases, on the other hand, the height of the cliffs is notably irregular, and such irregularities may be either original or secondary. Examples of original irregularities are :—

(*a*) the " rolls " of Glacier-Tongue which, as described later, may be due to seasonal variation (Plate CXXIX),

(*b*) pressure waves, haycocks, etc., cut through by the bounding walls, and

(*c*) barrancas due to thaw action (Plate CLXXV, Chapter VIII).

Secondary irregularities may be due to the incorporation in the tongue of sea ice carrying accumulations of snow, which will appear in the face of the cliff as saucer-shaped depressions. Bearing upon this question is the fact that no tide-crack could be seen in 1908 or in 1912 on the south side of the Drygalski Ice-Tongue, where it was crossed by Shackleton's Magnetic Pole Party and by the Northern Party of the Scott Expedition. A gentle snow slope marked the boundary between sea ice and tongue so far as eye could reach either way. When the sea ice south of the Drygalski Tongue breaks out in the autumn, it is probable that the tongue possesses sea cliffs that differ in height, both from time to time and from place to place, until, finally, the majority of the sea ice fringing it breaks away, leaving an undulating cliff of which the lower portions are composed of snow accumulated on sea ice in the indentations of the Ice-Tongue itself.

(*c*) *Appearance of the Wall.*

The appearance of the walls of different Ice-Tongues differs according to the structure of the ice of the tongue and particularly according to its air-content. Plates CXXX and CXXXI show cliff walls of the Barne Glacier and the Nameless Glacier, respectively. In the former case, the production of blue ice has been accompanied by a greater reduction of air-content than in the second. Yet both cliffs are of true ice, and similar contrasts probably account for the undue prominence given to the " névé berg " and " névé cliff " as constituents of Antarctic shore-ice. Plate CLI of Chapter VII again shows a portion of Warning Glacier-Tongue, showing true ice below and névé above. Plate CLII, Chapter VII, shows a portion of the face of the Newnes Glacier, showing " blue ice " below and " bubbly ice " above.

(*d*) *Surface of Ice-Tongues.*

Inequalities in the surface of an Ice-Tongue are reflected in its walls and have therefore been dealt with in the above paragraphs. The surface of the majority of the Ice-Tongues consists of snow, the deposition of which still exceeds ablation along many portions of the Antarctic littoral. One of the most striking features of the great Antarctic glaciers of South Victoria Land, as shown elsewhere, is the marked changes in their surface appearance. Originating in a gathering ground where alimentation less ablation is a plus factor, they descend to sea level through a zone where it is a minus factor, finishing their life in an area where it is generally a plus factor, the greater part of the denudation which results in their ultimate destruction taking place from below. Anomalies which occur, such as Glacier Tongue and Warning Glacier Ice-Tongue, are due solely to the drift-chiselling and ablative action of stormy winds. This is well

shown by the fact that, wherever a lee permits it, snow accumulates even on these exceptional Ice-Tongues.

The surface covering of snow which is thus normal to Ice-Tongues assists, of course, in hiding such inequalities of surface as are original structures brought into being by various agencies further up the glacier. One practical result of this is the principle that, in order to cross an Ice-Tongue with the least trouble, one should keep as far as possible from where it abuts upon the land. The greatest Ice-Tongue of the Ross Sea area—the Drygalski—has been crossed in two places by sledge parties. It proved to be deeply furrowed by steep-sided valleys named by David "barranças." When seen by one of the writers in the present Expedition, they appeared to be the result of pressure modified by thaw, but with their outlines accentuated by huge sastrugi and veiled in places by drifts. "Haycocks" and crevasses also were not uncommon, these being possibly "remainders" left from the ice-falls of the valley glaciers, but more probably caused by differential movement of, and pressure between, the different ice streams feeding the Drygalski Ice-Tongue, and, particularly, the David Glacier and the Confluent-Ice to the north of it. It is possible, also, that submerged rocks similar to, but lower than, the islands to the north may also cause local disturbances which add their quota to the pressure which is more marked here than in other ice streams of similar nature.

(*e*) *Movement of Ice-Tongues.*

Only in one case has direct measurement been made of the rate of movement of an Ice-Tongue, when the Mackay Glacier feeding the Mackay Ice-Tongue in Granite Harbour was found by Taylor and Debenham to be moving forward at the rate of, approximately, a yard a day in December and January, 1912. Signs of the movement of Ice-Tongues are, however, readily found where movement is appreciable, and three in particular may be mentioned as being of importance :—

(i) Cracks in neighbouring Fast-Ice.*
(ii) Pressure in Fast-Ice between an advancing tongue and fixed points in front of it.
(iii) "Rolls" in the Ice-Tongue itself.

During nine or ten months of the year, an Ice-Tongue in a sheltered bay is usually surrounded on three sides by sea ice. As soon as this ice takes the form of a coherent sheet it will present to the forward movement of the tongue an obstacle which, though yielding, readily records the pressure put upon it.

If the movement of the land ice is noticeable, two results will appear. The sheet of ice will be moved bodily forward away from the land against which it would normally rest, and the sea ice between the tongue and any fixed point, such as a cape, an island, or a stranded iceberg, will be thrown into folds and pressure ridges. The results of

* Fast-Ice is sea ice while remaining fast in the position of growth.

such an advance—the pressure "rolls" in the sea ice, the shear-cracks, and the gradual thinning out of the Fast-Ice towards the back of the bay near the root of the tongue—are described in the chapter on Fast-Ice (pp. 349-354). Reference is made to it here because, although it is difficult to obtain a direct measurement of the amount of the winter's advance of an Ice-Tongue from the study of these effects, yet it is quite feasible to obtain therefrom a good idea of the relative rate of advance of different Ice-Tongues situated in a similar environment.

Such a comparison has been made in the two cases of the Mackay Ice-Tongue in Granite Harbour and Glacier Tongue in McMurdo Sound. The effect of the former on the Fast-Ice of the bay is described in the pages to which reference is given above. The effect of the latter is seen in the heavy pressure ice off the tongue, and, still better, in the presence of a crack 30 feet wide, and still increasing when seen, north of the Turk's Head cliffs. This crack was covered with ice which gradually decreased in thickness until a thin black line of water remained to betray the fact that it was still opening. Debenham, who has studied both examples, considers that the effects in both places are of the same order of intensity, and that the rate of forward movement of Glacier Tongue is strictly comparable with that of the Mackay Glacier.

We have thus important evidence linking the two together which, in view of their similar shape, is highly suggestive. It should be noted here that Professor David, during the journey to the South Magnetic Pole in the Shackleton Expedition, 1907–1909, recorded very similar evidence towards the base of the Drygalski Ice-Tongue.*

A feature of Glacier Tongue which impresses itself on the observer, even at first sight, is the disposition of the ice as a series of "rolls," giving to it a surface and undulating outline which is very characteristic (Plate CXXIX). These "rolls" are about a quarter of a mile from trough to trough.

Similar "rolls" may be observed in the Nordenskjöld Ice-Tongue and are here of about the same length. Although neither of the writers has seen the Mackay Ice-Tongue, a close examination of photographs suggests that there is in this tongue also a comparable structure.

What is the significance of these "rolls"?

It is suggested here that they are probably due to seasonal variation, possibly a seasonal variation in output from the parent land glacier. If this is so, and it appears a feasible explanation, the length of one such "roll" should represent the forward movement of the tongue during a single year. It is therefore interesting that in glaciers, which from other reasons we believe to be moving at comparable rates, the length of the rolls appears to be comparable also. If anything, the rate of movement of the Mackay Ice-Tongue would appear to be slower than that of Glacier Tongue, and here, in a sheltered bay where there is probably a lee from the main Victoria Land current, denudation also might be expected to be less.

* David and Priestley, 'Shackleton Geological Memoir,' vol. 1.

General significance of Ice-Tongues as regards the Ice Girdle around Antarctic shores.

The effect of Ice-Tongues on the Antarctic Land-Ice and Sea-Ice girdle may be summarised under five headings :—

(*a*) Strengthening effect on Shore Land-Ice.
(*b*) Disruptive effect on Fast-Ice along a straight coast.
(*c*) Effect as " bars " across currents in preventing the formation of Fast-Ice.
(*d*) Collecting of Pack and Bergs on their windward and currentward side.
(*e*) Effect in holding up the movement of the Pack.

Of the above, (*b*), (*c*), (*d*), and (*e*) are discussed in the chapters on Fast-Ice and Pack-Ice and need no further reference here. The strengthening effect of Ice-Tongues on Land-Ice formations around the Antarctic shores is very evident. On a straight coast, rapidly moving Ice-Tongues will shear their way through the more stagnant Shelf-Ice and greatly weaken it, but in an indentation, however shallow, the effect will be strongly in the opposite direction. Ice-Tongues stretching out as converging fingers or piers will tend to trap the sea ice formed between them and hold it long enough for it to become burdened with a thick perennial coating of snow. In such a way, as mentioned in Chapter V, great Shelf-Ice formations have been built up in the past. Evidence of such a sequence of events is even now to be seen in the angle between the Drygalski Ice-Tongue and the Reeves Glacier, and Campbell-Priestley Confluent-Ice. Acting as the " ribs of a fan," these formations under such conditions may play a great part in building up the outer ice-formations in the advanced stages of the glacial cycle on a sea-bordered land mass.

Effect of greater Glacierisation on Ice-Tongues.

The process outlined above sufficiently indicates one effect of greater glacierisation upon Ice-Tongues. They are likely to lose their individuality to a large extent and become merged in a more uniform ice-girdle. The order of growth with increasing alimentation is shown in the classification adopted :—Expanded Foot-Ice to Piedmont-Ice or to Ice-Tongues, these again to Shelf-Ice of type A. One effect of progressive increase in thickness requires to be mentioned, viz., the fact that the erosive action of the glacier upon its bed will be prolonged seawards by a thickening of the apron where it leaves the land. Significant soundings off the Drygalski Ice-Tongue suggest a scooping out of the sea bottom to a depth of over 600 fathoms, whereas the normal depth of the continental shelf both to north and south is about 350 fathoms. This scooping was, however, probably carried out at a time when the coast was at a higher elevation than at present, since comparatively recent subsidence has certainly taken place along the whole coast.*

SHELF-ICE.

In the chapter dealing with the classification of ice-formations, Shelf-Ice was placed in a category by itself, for the reason that it lies within a " zone of balanced forces "

* This point will be dealt with in Chapter III, "Physiography, Robertson Bay and Terra Nova Bay," by R. E. Priestley.

where supply, movement and wastage all exist in the same zone and where none of the three is predominant. Supply, as usual, is in the form of precipitation, with some additions due to the outpouring of ice from the Land-Ice formations of the uplands, and wastage is by ablation and by the solvent action of the sea water on which it rests, as is the case with Ice-Tongues.

The occurrence of Shelf-Ice is of particular interest to the Antarctic glaciologist, in that the size of the sheets far transcends that of any other known ice-formation, with the exception of Continental-Ice, and because their occurrence is at present limited to the Antarctic regions. The occurrence of this type of ice-formation in large areas demands above all an adequate supply of locally deposited snow, coupled with temperature and salinity conditions in the sea water, such that solution of the Shelf-Ice will not proceed at too great a rate. These two conditions differ from the conditions affecting alimentation and denudation of Land-Ice formations, because of the paramount importance of coastal precipitation and of the denudational effect of sea water. It appears probable that suitable conditions are only met in Antarctic waters, and that this type of ice-formation cannot at present form in Arctic seas, owing to the relatively unfavourable temperature and salinity of the North Polar seas.

The suggestion has been made elsewhere that the blue ice characteristic of valley glaciers owes its occurrence largely to the dry winds sweeping down the glaciers from the Plateau. Towards the foot of the glacier close to sea level, on the other hand, conditions are quite likely to become more favourable to an excess of precipitation over ablation. However this may be, and whatever may be the cause, the fact remains that the portions of a glacier which reach sea level are usually snow-covered, and this is particularly true of the almost level ice masses which extend far from land and which lie only about 100 feet above sea level.

The grandest example of this type of ice-formation is the Ross Barrier* (Plates CXXXII and CXXXIII), but the ice mass to which Nordenskjöld gave the name *Shelfeis*† is obviously similar in many respects, though our knowledge of this formation is much less complete than our knowledge of the Ross Barrier.

Since the discovery in 1841 by Sir James Ross of the huge ice-formation bearing his name, which barred his way to the south, no single geographical feature in Antarctic regions has excited so much interest or been the cause of so many speculations. Notwithstanding this interest and the fact that it has been many times traversed, our knowledge of the glaciology of the Barrier has been but little advanced.

The labours of Sir James Ross delimited the northern boundary; the expedition of Borchgrevinck established the fact that the glacier had receded between 1841 and 1899. This latter fact was confirmed by the late Captain Scott in the Discovery Expedition of 1902, when, by soundings and measurements of the height of the seaward edge, this

* Maps I and II.

† Shelf-Ice of this type has not been examined by the writers. It is recognised as a sub-type under the name of Shelf-Ice of type B, and its method of formation is discussed shortly in Chapter V. For further details readers are referred to the original description of its discoverer, Dr. Otto Nordenskjöld, in his memoir, 'Die Schwedische Südpolar Expedition und ihre Geographische Tätigkeit.'

edge was shown to be afloat. Observations from a balloon showed that the Barrie was not uniformly level, but that the upper surface was bowed into waves which here, at the seaward edge of the eastern portion, ran about east and west. The distance from crest to crest of the undulations was found on a short sledge journey to be about 3 miles. Later observations by Captain Scott, Shackleton, and, finally, by Amundsen, on sledge journeys, have roughly delimited the boundaries, and showed that the Barrier, though generally level, is thrown into huge pressure ridges in the vicinity of land and, particularly, near the glaciers leading down from the Plateau.

With our present knowledge, the Barrier may be taken as a snow-laden sheet of ice about 500 miles wide and 400 miles broad, afloat at the seaward end, with a height at the terminal face varying from 6 feet to 160 feet. The total area of this sheet cannot be far from 150,000 square miles.

Though the Ross Barrier is by far the largest floating ice-formation known, other floating sheets of a different type are common in the Antarctic, and have been discussed earlier in the chapter. The extension of a glacier into the sea in Antarctic regions is in fact the rule, provided the movement of the glacier is sufficiently rapid; and such a glacier will extend into and float on the sea, until the loss at the seaward end is sufficient to balance the forward movement. The loss at the terminal face of land ice is comparatively insignificant in these latitudes, unless the ice is afloat and the seaward portions can be undermined and broken off to float away and expose a fresh face to the action of the sea water. The formation of a floating extension is, therefore, a sure indication that the rate of advance of the glacier is rapid, and, other things being equal, the longer the extension the quicker must be its rate of movement seawards.*

As will be seen later, this seaward movement is compounded of two—(1) that due to the thrust of the land glacier or glaciers behind the floating portion, (2) that inherent in the floating portion of the glacier, which tends to expand outwards under its own weight, just as a piece of tar lying on a flat surface tends to flatten and thin itself. A gradient, either on the upper or lower surface, is not necessary for the initiation of the spreading action, which, however, obviously does not assume importance until the dimensions of the floating portion of the Ice-Tongue or Shelf-Ice are considerable.

That the seaward portion of the Ross Barrier is afloat is conclusively proved by the measurements of the height of the terminal face and by soundings, as also by the fact that Shackleton's vessel, "Nimrod," when moored alongside the Barrier, moved up and down with the tide exactly in unison with the Barrier.

If further proof were needed, it is furnished by the quick retreat of the Barrier since first sighted by Ross in 1841, as it is obvious that no such rapid loss from the seaward face would be possible unless the seaward portion of the Barrier were afloat.

Soundings and Barrier heights are shown together on Map II.

That the retreat of the Barrier continues is indicated by the disappearance of Balloon Bight between 1902 and 1908.

* This question has been discussed under the heading "Ice-Tongues."

Though this considerable change has taken place in the eastern portion of the Barrier, the western portion of the Barrier seems to have remained almost unchanged since 1902, and, according to Debenham, a comparison of photographs and sketches taken at Cape Crozier in 1902 and in 1911, shows that, in this period, the Ross Barrier at its extreme western edge has, in fact, advanced slightly.

Crevasses, Pressure and Movement.

As we have already stated, the formation of crevasses is to be referred in all cases to the occurrence in the body of the ice mass of tensions which are too great to be accommodated by movements of the ice molecules, so that rupture is caused. Such rupture occurs on the Barrier only in the neighbourhood of land, or along a line joining two points of land which divides the Barrier into portions which act and move independently of one another. The series of crevasses along the line drawn from White Island to Cape Crozier are of the latter type, and they mark the boundary between the relatively stagnant portion of the Barrier lying between White Island and Ross Island and the main body of the Barrier, whose motion is much quicker. Other types of crevasses which have been observed on the Barrier can be referred, either to the proximity of outlet glaciers leading from the Plateau, causing a differential movement of the Barrier ice, or to the fact that the Barrier ice is locally resting upon firm land, or touching the sea bottom. The crevasses met by Amundsen during his journey to the Pole, 46 miles south of Framheim, are apparently of this type.

Pressure ridges or waves are invariably associated with crevasses of the last type, these waves lying roughly at right angles to the direction of movement of the Barrier. The height, wave-length, and number of these pressure waves will be a function of the velocity of movement and of the Barrier thickness, and the approach to a glacier while sledging on the Barrier will be announced by the occurrence of pressure waves whose amplitude increases as the glacier is neared. The greater the velocity and volume of the glacier, the further out will the pressure waves first become appreciable.

Where the Barrier meets an obstruction, such as that postulated as causing the crevasses observed by Amundsen, pressure waves will be formed parallel to, and on that side of, the obstruction which faces the direction of advance of the Barrier. Somewhat similar are the heavy pressure ridges formed at Pram Point, near Hut Point on Ross Island, where the movement of this confined portion of the Barrier is obstructed by the land. These pressure ridges at Pram Point are not very numerous, but comprise several well-defined waves about 150 feet from crest to crest and 30 feet in vertical distance from crest to hollow. Similar, but larger, pressure waves line the southern and eastern portions of Ross Island, especially near Cape Crozier. The general run of these ridges is shown in Map III.

Mention has already been made of the pressure waves (running nearly east and west) observed by Captain Scott near the seaward edge of the Barrier; but in general one of the most striking characteristics of the Barrier far from land is the extreme flatness of its surface, neglecting the minor rugosities caused by wind action.

On the Barrier journeys of the present Expedition, however, ridges were observed which appeared to be somewhat similar to those referred to above. It was estimated by us that these ridges measured about 1½ miles from crest to crest, and were about 10 feet in height.

The only other pressure ridges met on the Barrier far from land by the present Expedition were those first observed in latitude 82° 30′ S., which were caused by the thrust of the Beardmore Glacier against the Barrier. These ridges were first observed about 50 miles from the mouth of the Beardmore Glacier and increased in size as the glacier was approached, until the height of the ridges must have approached 40 feet, with a distance of some 2 miles between crest and crest.

As the glacier was more closely approached, the ridges apparently became less pronounced, no doubt due to the fact that the parties ascended the glacier through The Gap (a comparatively stagnant branch separated by Mount Hope from the main body of the glacier) and did not, therefore, traverse the main pressure area. The violent blizzard and heavy snowfall experienced early in December at the foot of the glacier undoubtedly partly filled up the hollows of any pressure waves which may have existed close to The Gap.

The route followed by the present Expedition on the journey to the Pole gave few opportunities for observations on crevasses and pressure, the route being chosen by Captain Scott so as to avoid these pitfalls as much as possible. Thus, the first "leg" of the journey on the Barrier, from Hut Point to Corner Camp, was designed to cut the line of crevasses running from White Island to Cape Crozier at a large angle, and to carry the turning point such a distance beyond this line that no crevasses would be met on the remainder of the journey, until the Beardmore Glacier was approached. The route chosen was an excellent one from this point of view, no crevasses whatever being seen from Corner Camp southwards.

No observations were made of the Barrier movement approaching in accuracy those measurements we owe to the Discovery and Shackleton's 1908 Expeditions. This measurement gave a movement of 492 yards per year (4 feet per day) in a direction N.30°E., at a point about 9 miles east of Minna Bluff. This figure is an average for the 6½ years which had elapsed between the laying of a depôt by Captain Scott and its rediscovery by one of Shackleton's sledge parties. In this observation of movement the motion was referred to fixed points on land, while in the present Expedition the courses made lay far from land. Astronomical locations of the depôts laid at Corner Camp and Bluff Depôt in 1911 and 1912 did, however, show a movement of the same order as that given above, but the result, though in excellent agreement with the previous one, can lay little claim to accuracy. It is interesting to note that sketches showing Mount Discovery behind White Island, made at Corner Camp in 1911 and 1912, indicated this movement in the most striking manner.

On the other hand, it is stated by Amundsen that no movement of the Barrier was detected at his winter quarters at the eastern end of the Barrier. This result is no doubt to be referred to the presence of land slightly to the south of that station, which

was indicated by an increase in height of the snow surface to 258 metres, and was associated with crevasses and pressure ridges on the Barrier surface.

No observations have been made of the movement of the Barrier midway between the two points, but, from general considerations, it seems unlikely this will be less than 4 feet per day, the figure representing the movement of the Barrier in the extreme west. In any case, the mean rate of northward movement can hardly be less than 3 feet per day.

Though all observers unite in reporting the presence of undulations on the surface of the Barrier at particular points, these undulations are not pronounced, except in the special localities mentioned. That they are not easily visible can be understood from the fact that the distance from crest to crest may be as much as 3 miles. Even, however, if the whole surface of the Barrier were undulating, the tendency of the prevailing winds would be to fill the hollows with drift snow. That this effect may assume importance seems clear from our observations on the sea ice at Cape Evans. This ice, in the spring of 1911, was seen to be marked by a series of undulations roughly parallel to the shores, measuring more than 100 feet from crest to crest, but with an amplitude of less than 1 foot. Notwithstanding the small difference in height between hollow and crest, the hollows could be recognised after each slight deposit of wind-driven snow, by the fact that the whole of this new snow lay in them (Plate CCXXXIV, Chapter X).

Besides these pressure undulations on the Barrier surface, which will themselves tend to become filled as a result of drifted snow, the wind operates everywhere in the formation of the "sastrugi" described in Chapter I. Areas of the Barrier which are constantly exposed to strong winds, whether carrying snow or not, will present a comparatively hard and uneven surface to the traveller, while areas which are seldom visited by violent winds will present a soft but level surface, provided there is here a sufficient snowfall, which is usually the case.

Map III shows the directions of sastrugi on the Barrier as observed by our Expedition, and the areas where sastrugi were not pronounced. Where the sastrugi are "mixed," *i.e.* indicating the occurrence of high winds from various different directions, we should expect *a priori* that the amount of retained snow would be a maximum.

Thickness and Structure of the Barrier.

Dr. Simpson, in his Meteorological Report (vol. 1), has dealt with the aneroid observations taken on the various sledging journeys, and has reduced these so as to show the difference between the barometric height at Cape Evans and on the Barrier on the course followed by us on the Polar journey. For details, the original memoir should be consulted. As head winds were constantly met along the route followed, it is probable that the pressure gradient on this course is small.

If, moreover, a pressure gradient along the course followed on the Polar journey exists, it must be of such sign that the pressure increases towards the south. This increase, if existent, will tend to make the Barrier heights deduced from barometric readings too small, but the magnitude of this discrepancy can certainly not be very grea

We may, therefore, conclude that the height of the Barrier increases from the Barrier edge close to Hut Point comparatively quickly, until latitude 79° S. is reached, the Barrier surface south of 80° S. being sensibly level, but possibly rising slightly as one proceeds further south. Beyond 80° S. latitude, the Barrier surface is not less than 170 feet 52 metres) above sea level. The corresponding figure derived by Mohn* for the mean Barrier height on Amundsen's journey on a different route is 60 metres, a figure which is in close agreement with that given above.

It is not without interest to observe that the Barrier heights derived by Mohn from observations by Amundsen show considerable variations, rising to 258 metres only 40 miles south of Framheim, the height being generally less south of 81° S. than north of this latitude. There can be no question that this considerable height just south of Framheim is due to the fact that the Barrier here rests on the ground, this inference being supported by the occurrence of pressure and crevasses about 46 miles south of Framheim. From 80° S. to the south, on the course followed by Amundsen, there are no very large variations in the Barrier height, the mean height between 80° S. and 81° S. being almost 100 metres, but a lesser height was observed further south, the minimum being at 82° S., with a height of only 35 metres.

These figures for Barrier height can lay no claim to great accuracy, being derived from simultaneous observations of the barometric height at widely different positions, or by calculation from the observed change in barometer reading in journeying from camp to camp. There seems no reason, however, to doubt the conclusion that the Barrier surface is fairly level except in the neighbourhood of land.

The evidence for the statement that the Barrier is afloat at its seaward face has already been given, and appears to be quite conclusive. It cannot, however, be assumed that the Barrier is also afloat far from its seaward edge without further investigation. We have no accurate knowledge of the mean density of the Barrier, which would enable us to estimate what proportion of the Barrier lies below sea level and what above sea level, but certain deductions can be drawn from other sources. Soundings, which have been made in the vicinity of stranded Barrier bergs on this and on previous expeditions, seem to show fairly clearly that such a berg floats with about one-fourth to one-fifth of its thickness above and three-fourths to four-fifths below sea level. The observations made by the Shackleton Expedition, when digging out the site of Scott's Depôt A near The Bluff, showed that 8 feet 2 inches of snow had been deposited in 6½ years and that this snow had a mean density of 0·5. At greater depths, one would expect the density to be greater, and there is, therefore, no reason to doubt the accuracy of the figures derived from the soundings around stranded barrier bergs.

A careful series of sextant observations of the height of the Barrier was made by the officers of the "Terra Nova" on the present Expedition, the heights observed being shown on Map II.

At no point was the height of the Barrier above sea level, where observed, greater than 160 feet. In general, the heights observed by the present Expedition are in

* Roald Amundsen's Antarctic Expedition—Scientific Results—Meteorology.

agreement with those of the previous Shackleton Expedition, except as regards that portion of the Barrier in longitude 172° E., where the height observed by the present Expedition was only 138 feet, or 100 feet lower than the height recorded by the Shackleton Expedition. This disagreement is somewhat surprising, in view of the agreement elsewhere, both in plan and elevation, and suggests the possibility of an error in the first observations, though there is always the chance that a single very high portion of the Barrier was missed in this area by the present Expedition, or had been broken off in the interval.

The total variation in height observed by our Expedition was from 6 feet to 160 feet, the former figure being observed in an inlet which obviously corresponded to the trough of one of the waves on the surface of the Barrier.* In the previous interval between the first Scott Expedition and the first Shackleton Expedition, a large portion of the Barrier near Balloon Bight had disappeared, while between the first and second Expeditions by Scott some general advance may have taken place.

Even if the assumption is made that the density of the Barrier is much greater than seems conceivable, the soundings made at the Barrier edge show that, here at least, the Barrier must be afloat. No direct measurements of the density of the ice in true Barrier Bergs is on record. From the appearance of the seaward face of the Barrier, it seems that it is formed either of névé or of white bubbly ice, though the Shackleton Expedition reports the appearance of clear ice near Framheim. This is not surprising, in view of the presence of pressure ridges and crevasses a few miles to the south, indicating the presence of land upon which the Barrier here rests.

Temperature, Humidity, Precipitation, Ablation and Erosion.

The air temperature on the Barrier is known with a certain degree of accuracy and, as shown by Dr. Simpson,† the temperature curve lags only eight days behind the insolation curve, the temperature in spring rising at almost the same rate as it falls in autumn, and the coldest and warmest days being almost at midwinter and midsummer. In all months, the temperature on the Barrier is colder than at Cape Evans, the difference being, however, greatest in winter and very small in summer. Thus, the yearly variation of temperature is large on the Barrier, the summer temperature, being, however, little below that at Cape Evans. Similarly, the amplitude of the daily variation of temperature in summer is very large on the Barrier, the maximum temperature being slightly lower than that at Cape Evans, but the minimum temperature considerably lower.

As Dr. Simpson has pointed out, these differences between Cape Evans and the Barrier are primarily due to the difference between the two surfaces—ice-covered or ice-free sea at Cape Evans, and snow-covered ice on the Barrier. The large amplitudes on the Barrier are easily seen to be the result of the low specific heat, and low heat conductivity of a snow surface, in comparison with solid ice or water.

* The same inlet has persisted in the interval between the Shackleton and Scott Expeditions, indicating that no great change has lately taken place on the seaward edge in this region.

† 'Meteorological Report,' vol. 1, pp. 84–86.

The reason for the maximum temperatures falling very closely together might conceivably be the fact that the upper temperature limit is set by the melting-point of ice and snow, were it not that the temperature very seldom rises to freezing-point in these latitudes.

It is probable that an additional reason for the difference in temperature variations in the two places lies in the fact that convection currents will be far less powerful at the lower (" night ") temperatures of the Barrier, so that the minimum air temperature closely approaches the snow temperatures at this time, while at times of maximum temperatures, much of the heat given by the surface to the air is carried upward by convection currents.

It is further necessary to explain why the Barrier temperatures remain almost unchanged during the winter months, while radiation from the surface continues most active. The explanation is that the proximity of the Ross Sea, and the frequent blizzard winds, cause a most effective mixing of the upper and lower strata in the atmosphere, so that the mean temperature of the Barrier in winter is governed by the temperature of the air some three or four thousand feet above the Ross Sea, which is itself governed by the temperature of the sea water below. Very cold and comparatively warm periods, therefore, alternate on the Barrier during the winter.

An important point of interest to Antarctic travellers is that the days of equal mean temperature on this snow-covered expanse are almost equally distant from mid-winter's day, so that the best date for the start of a sledge journey under given conditions can readily be calculated.

It is of very great importance to obtain fuller information regarding the percentage humidity and vapour tension of the Antarctic atmosphere, in view of their effect upon the rate of ablation of the snow surface, since such information as is available is not too reliable. Almost invariably, it was observed during the winter at Cape Evans that there was considerable evaporation from exposed ice surfaces during blizzard winds, even when snow was apparently falling during a large part of the blizzard. This can only mean that, at Cape Evans in these conditions, the air was not wholly saturated with water vapour, suggesting that the air had descended in the immediate vicinity of the station. In addition to this loss, there is the erosional action of the wind-borne drift in " chiselling " away the surface. If this result is equally true on the Barrier and true during the summer months, it will involve a considerable ablation even during many blizzards.

The most complete measurements of percentage humidity are those due to Amundsen, the conditions at whose winter quarters approximated to those on the Barrier so far at least as temperature was concerned. Amundsen found that the percentage humidity reached a maximum in July and August and a minimum in November, the mean humidity varying from 90 to 73 per cent., and the mean vapour pressure varying from 0·1 mm. in August to 2·4 mm. in December. The driest wind was from the south, the wettest winds (which were also the least common) blowing from the north and north-west.

We cannot assume that these conditions hold on the Barrier at a distance from its seaward face, though there seems some likelihood at least that, apart from drift snow caught in the lee of any inequalities on the surface, the net gain to the Barrier surface during winter blizzards is not large. This was undoubtedly true during the winter of 1911. Amundsen, in fact, reports drifts only 1½ feet high formed in the *lee* of his depôts during the winter.

Our own Polar sledge parties, though noting heavier drifts in the lee of cairns and depôts (a drift 100 feet long and 10 feet high at the large "One Ton" Depôt) observed that small objects dropped in the preceding autumn, 9 months before, opposite Minna Bluff were only covered with 4 inches of soft snow. The conditions were quite otherwise in the following year (possibly due to the more open conditions in the Ross Sea), and the drifts were *very* much heavier in the lee of cairns visited by the search party.

Considering all the evidence which is available, it seems more than probable that the greatest additions to the Barrier surface take place in the summer months, probably during two or three fairly heavy snowstorms, denudation slightly exceeding precipitation during the remainder of the year. Light snowfalls also frequently occur in the summer months, but the total amount of snow precipitated on these occasions appears to be small.

No further information is available as to the absolute magnitude of the annual precipitation on the Barrier, or the loss from the Barrier surface due to evaporation, wind and other physical causes. The only valuable piece of evidence regarding the difference between the addition to the surface and the subtraction from it, is that due to the rediscovery of Captain Scott's Depôt "A" by the Shackleton Expedition, and the sledge party who stumbled across this Depôt are to be congratulated in having extracted the maximum good from an accidental *rencontre*.* They dug down to the Depôt, and ascertained that in the interval of 6½ years, 8 feet 2 inches of snow had accumulated on the surface, of average density 0·5, or an average annual increment of 7·5 inches of water.

This figure is almost certainly too large, as the growth in the neighbourhood of any obstruction (such as a depôt) is much greater than the growth on a level undisturbed surface, due to the drift carried by winds and deposited in the lee of the obstruction. A single snowfall has been known to add locally 2½ feet to a level surface, corresponding to about 4 inches of rain. Such occasions are, however, rare, and it is unlikely that the average annual precipitation on the Barrier exceeds 20 inches of rain, the greater part of this precipitation being removed by ablation and wind erosion. It is also impossible to estimate the magnitude of the denudation from the surface due to wind action, but cases are not uncommon where 1 foot, or even more, has been locally taken from the

* Ernest Joyce was in command of the party and Ae. L. A. Mackintosh, an officer of the "Nimrod," was responsible for the observations. The incident is one of the most striking on record of the way in which non-scientific members of Antarctic Expeditions have appreciated the value of, and have added their contributions to, glaciological work. (*See* Foreword.)

surface and blown northward, to be deposited either in the sea or on the Barrier further to the north. It is considered that this factor is at least as potent in the process of denudation as the loss due to evaporation from the surface.

The effect of wind, both on precipitation and ablation, is, we consider, of decisive importance. The evidence goes to show that both factors vary in opposite directions (but tending, of course, towards the same result) in different situations. The accumulation of snow on the Barrier is likely to be very patchy, and areas where precipitation is above normal are areas where ablation is likely to be below normal.

In addition to the changes taking place on the upper surface, alterations take place to the seaward face of the Barrier, and it is known that, since the Expedition of Sir James Ross in 1841, the Barrier face has retreated about 25 miles on the average. Since 1902 there has been little change on the whole, though comparison of maps gives some indication of a readvance. If we had more accurate measurements of the general rate of advance of the ice, it would be possible to estimate fairly exactly the annual loss which must take place through the discharge of icebergs to bring about the neutralisation of this forward movement. The manner in which these bergs are annually broken off from the face shows that the prime cause is melting by the warm water lying beneath the Barrier, which is most effective close to the edge. This action suggests the presence of a warm current from the north in the lower layers of the Ross Sea.

If the sea water under the Barrier were stagnant, effective equilibrium between temperature, salinity and pressure would exist where the Barrier ice is in contact with sea water; but, if there is a warm ocean current circulating beneath the Barrier, the under surface of the Barrier must melt to some extent. No information is available which would enable us to estimate the amount of this melting. A point, however, to notice, is that a local increase of precipitation on the highest part of the Barrier surface would depress the under surface locally, if afloat; this would upset the equilibrium between ice and sea water, and melting would proceed until equilibrium were once more established.

Granted a uniform circulation of sea water beneath the Barrier, it is clear that melting must take place at the under surface, and that this action will be most energetic—

(1) at the seaward edge, where the current first meets the Barrier;
(2) on those portions of the Barrier (even far from the seaward edge) where the Barrier is of greatest thickness.

We know that the Barrier is melting at its seaward edge and it is this which causes the formation of Barrier bergs and prevents the Barrier edge from advancing to the north. There must, therefore, be a current washing the northern edge. There is a strong surface current which drives the bergs to the north, and this suggests that the current from the north is in the nature of a migration of the sub-surface water to take the place of the surface water driven north by the predominant southerly gales. This seems to the writers to offer the only plausible explanation of the fact that the Barrier does not increase notably in height as land is approached to the south.

Let us consider for a moment what would be the state of affairs if the Barrier were aground at a point (say) 100 miles from the back of the Ross Sea, remembering that—

(1) a considerable volume of ice pours down the Beardmore and other glaciers to add its bulk to the Barrier;

(2) the "flattening" action of a mass of ice in this latitude depends very largely on the temperature, and to some extent on the pressure. It is therefore greatest in the case of a mass of ice resting on warm sea water.

If the Barrier were aground within 100 miles of the Beardmore Glacier, the slope of the lower surface would necessarily be small, because the slope of the upper surface, is known to be very slight. The tendency of this mass to spread seaward would be slight, and it seems impossible that the thrust of the glacier behind could overcome the friction and set the Barrier in reasonably swift motion without the mass of ice pouring down the Beardmore Glacier piling up to a very considerable thickness near the glacier mouth. In fact, quick forward movement in an ice mass resting on land demands an appreciable slope of the upper ice surface.

Further, the "flattening" of an ice mass, with a lowering of the upper surface in the process of flattening, involves a spreading out of the mass to those directions in which it is unconfined by land. The quickest moving portion of the Barrier is that which is nearest the seaward edge, and the slowest moving that which is close to land. Given a more or less uniform snowfall, therefore, there should be a rapid increase of height as land is approached, unless, either melting takes place below at the greatest rate where the thickness is greatest, or the rate of "flattening" increases enormously with a small increase of thickness of the ice mass. Both these actions will be simultaneously effective if the ice mass rests upon water at freezing temperature, but cannot operate effectively if the mass rests upon land, where the mean temperature of the year is below zero Fahrenheit. May it not indeed be, that the comparative thinness of the Barrier between Ross Island and White Island is caused by a more effective subglacial water circulation here than elsewhere? Certainly it would be strange if the yearly permanent snow addition in this neighbourhood were eventually found to be much less than that which remains on the surface in the centre of the Barrier.

Under conditions of greatly increased precipitation, greatly decreased ablation or decrease in sea temperature, the Barrier might slowly increase in thickness until it rested on the ground; the growth in thickness would then become rapidly accelerated—

(1) owing to the fact that melting could no longer proceed from below;

(2) owing to the fact that the rate of movement seaward would notably decrease, partly in response to the lower basal temperature and partly to friction on the ground.

Certainly the comparative freedom from crevasses and pressure far from land seems to indicate a real lack of differential movement, while one would certainly expect to meet much more crevassed areas if the Barrier rested upon the ground, either wholly or in part.

It is unfortunate that opportunities were not afforded on this Expedition to take serial temperature measurements in crevasses near the Beardmore Glacier, as this would have given evidence of a most definite character.

It has been generally assumed, since the upper surface of the Barrier at some period lay at least 800 feet up the slopes of Ross Island in the region of Cape Crozier, that the general height of the Barrier above sea level must have been not less than 800 feet higher at one period in the past. This would have been sufficient to cause the Barrier to take ground, at least in places, at its present seaward edge. This deduction as to previous height cannot, however, be drawn, since the thrust from behind would certainly have forced that portion of the Barrier which abutted Ross Island far above the general level of the Barrier surface. The sketch shown on p. 128 of the Shackleton Memoir (Geology) clearly indicates that this action takes place to some extent at Minna Bluff even at the present time.

With such evidence as is at present available, it seems desirable to make certain numerical calculations, in order to throw light on the equilibrium conditions obtaining at present. For the purpose of these calculations, we will take the following figures :—

Average height of Barrier above sea level (inland), 150 feet; northern edge, 120 feet.
Total thickness of Barrier (inland), 750 feet.

Average annual excess of precipitation over surface denudation, 15 inches of snow of density 0·5.

Average rate of movement at the seaward edge, 1500 feet per year.

We will further assume that the Barrier everywhere floats on the sea for a length of 260 miles and a breadth of 320 miles, the movement of the Barrier being everywhere constrained except towards the north, or more accurately towards the N.N.E.

The Barrier is thus considered to be a mass of compacted snow, or ice, 600 to 750 feet thick, whose bottom is at a temperature slightly below freezing-point and whose temperature gradually decreases towards the surface. Under these conditions, the Barrier will tend to flatten itself, thinning and spreading towards the seaward edge at a rate which is dependent on the thickness of the ice. No accurate information is available regarding the viscosity of compacted snow or ice under these conditions, which would enable a rough calculation of the rate of movement to be made. In view, however, of the known rapid increase in viscosity of ice as the melting temperature is approached, we have no reason to be surprised that the movement due to the weight of the Barrier under these conditions approximates to the rate of motion of land glaciers lying on sloping beds in more genial climates, and that it far exceeds the observed rate of motion of such stagnant glaciers as the Ferrar Glacier, or the Barne Glacier, in approximately the same latitude.

In some measure, this movement under gravity must be added to by the thrust of such glaciers as the Beardmore, the Shackleton, Liv's Glacier and others, and it is known that the thrust of these glaciers causes the formation of heavy pressure ridges for a distance of many miles from the glacier outlet. An estimate of the volume of

ice added daily to the Ross Barrier in the month of December by glaciers on the western shore has been made in the Geological Memoir of the first Shackleton Expedition, and the figure finally accepted is 10^9 cubic feet daily during this month. The figure given is based on the known speed of the fast-moving Mackay and Drygalski Glacier Tongues in somewhat lower latitudes, on an estimated breadth of glaciers along the western shore of the Ross Barrier, and on an estimated thickness of the glaciers in question. It is the latter estimation which is most open to question. Whatever value this estimation may have, a probable figure will be given if we assume a mean thickness for the glaciers in question somewhat greater than that of the Barrier (say, 2000 feet).* The total width of the glaciers in question is 62 miles, which gives a minimum discharge into the Barrier on its western shore of (in round numbers) 2×10^9 cubic feet. This figure may be doubled to account for other glaciers on the southern and eastern boundaries, giving a discharge into the Barrier from the plateau of 4×10^9 cubic feet daily, *in the middle of the summer*.

The average for the year will certainly be less than this, and cannot exceed 2×10^9 cubic feet daily.

The increase to the surface of the Barrier may be taken as (roughly) 15 inches of compressed snow per annum of density $0 \cdot 5$, or (say) 9 inches of snow of the mean Barrier density. This gives an increase of (say) 6×10^9 cubic feet per day, which we think is probably too high an estimate.

The daily loss from the Barrier edge during the last few years (while the edge has remained nearly stationary) is given directly from the mean rate of movement, the breadth of the Barrier, and its mean thickness at the edge. The figure given by this calculation is $4 \cdot 8 \times 10^9$ cubic feet per day.

To this must be added the daily loss due to melting of the Barrier on its under surface, a quantity which is absolutely unknown.

Denoting this by M, we can write down the following equation, which will represent the facts to a first approximation :—

Additions to Barrier by glaciers plus additions to surface minus loss at seaward edge of Barrier $= \text{M}$ or $\text{M} = 2 \cdot 0 \times 10^9 + 6 \cdot 0 \times 10^9 - 4 \cdot 8 \times 10^9$ cubic feet.†

Obviously, these figures can possess little claim to accuracy, but they at least indicate that some melting must proceed from below, and that the amount of this is at least comparable with additions to the upper surface, and of the same order as the probable additions to the Barrier due to the advance of glaciers leading from the Plateau.

The figures published in the Shackleton Memoir differ considerably from those here given, but it seems certain that the average contribution from glaciers could hardly exceed 2×10^9 cubic feet per day. In the memoir referred to, the assumption has been made that the mean thickness of the Barrier at its seaward edge is 720 feet. This figure seems to us somewhat excessive. If this figure of 720 feet should, however, be correct,

* Especially as the measurement of velocity refers to the surface layers of the glaciers.

† This is on the assumption that there is at present no significant change in the position of the terminal face of the Ross Barrier.

it would mean that the amount of melting which proceeds on the under surface of the Barrier must be smaller than that here deduced. An accurate knowledge of the mean density of the Barrier and the thickness is, in point of fact, of vital importance, and it is hoped that any future expeditions in this sector will be able to pay particular attention to this point.*

It is a point of no little interest to note that the height above water level of floating Shelf-Ice and Ice-Tongues in the Antarctic, though variable, tends to reach an upper limit, which is not exceeded even in the case of the largest of these. It might be said that this height is in some way conditioned by the presence of the continental shelf, but a little consideration suggests that this can hardly be the case.

Let us fix our attention on a point on the under surface of the Barrier where it rests upon sea water. The temperature of the sea and ice must be related to the salinity of the sea water and to the hydrostatic pressure in such a manner that all are very closely in equilibrium, *i.e.* so that there is no very great amount of deposition or denudation of the under surface during the year, except near the Barrier edge, where erosion undoubtedly is very effective. Further inland, the amount of denudation must be considerably less, and must be conditioned by the presence of a water circulation under the Barrier, as, otherwise, the constant loss of heat by conduction through the Barrier to the air above would result in additions to the under surface. The melting of the ice, where the current meets the under ice surface near the Barrier edge, both cools and dilutes the sea water, so that, further inland, the salinity must be less and the sea temperature lower. The capacity of the sea water for melting the under surface therefore decreases with the distance the water has travelled beneath the Barrier, but cannot be greatly lessened if the total volume of water is great and there is effective horizontal and also vertical circulation beneath the Barrier (*i.e.* if the colder, but less saline, water formed by melting ice sinks and is replaced by warmer and more saline water from below).

In the absence of accurate knowledge regarding the conditions which obtain beneath the Barrier, it does not seem worth while pursuing this matter further, except to note that the temperature of the under surface of the Barrier cannot be far from $-2°$ C., a temperature at which the viscosity of ice is much less than at temperatures a few degrees lower. In our opinion, it is to this fact that the Barrier largely owes its comparatively rapid movement. We may almost infer that it is this circumstance—that the temperature of the under surface, bearing with it the load above, is only a little below 0° C.—which limits the height of such examples of Shelf-Ice as the Barrier. An increased supply of snow to the surface of the Barrier would soon increase the pressure upon the under surface; this would cause a greater velocity of movement which would tend to thin the sheet of ice. A glance at the curve shown in Fig. 179 (Appendix) will make the matter clearer. It will be seen that, provided the pressure on the Barrier's

* Serial sea temperature and salinity observations should throw considerable light on the latter. It seems probable that acoustical methods (by time intervals before the arrival of an echo, as experimented with by the French for sounding) might be used to measure the thickness of Barrier, or land glaciers.

under surface is sufficiently great at the temperature of the sea water, an increase of even a few feet of snow on the upper surface of the Barrier might be sufficient to double the rate of seaward movement of the Barrier.

In certain conditions, a truly enormous snowfall would be necessary in order to increase the thickness of the Barrier even slightly. This may be an explanation of the fact that the height of the floating Ice-Tongues and Shelf-Ice observed does not exceed a certain moderate value.

On this view, a notable increase to the Barrier surface, caused either by increased deposition or increased supply from the glaciers fed by the Plateau, would cause the Barrier to increase somewhat in thickness, to move much more rapidly,* and, by virtue of its increased momentum, to rise well up on Ross Island, but this increase would not be sufficient to cause it to take ground anywhere along its present seaward edge, except possibly in the most extreme case imaginable.

It must be admitted that there is definite evidence that Mount Hope, at the mouth of the Beardmore Glacier, was at one time overridden with ice ; this does not, however, prove that the Barrier surface (except very close to the Beardmore) reached that height. It only proves that the Beardmore Glacier discharged in the past a greater volume of ice into the Barrier than it does at present.

Origin of the Barrier.

There can be little doubt that the formation of the Ross Barrier, in the first place, owes much to the glaciers typified in the Beardmore, which must have been continued in the form of long floating Ice-Tongues stretching into the waters of the Ross Sea, exactly as does the Drygalski or Nordenskjöld Ice-Tongue to-day. The Barrier might, in fact, conceivably be due to the coalescence of many such Ice-Tongues, all pushing out from the land. It seems certain, however, that the climate to which the glaciers owed their power would operate similarly at sea level, so that sea ice would be formed in all quiet backwaters. This Fast-Ice might finally not be dispersed during the summer months.† The continual addition of snow *in situ* would then add notably to the thickness, which might also be supplemented by growth from below, to some extent at least, until finally the Barrier grew to the maximum thickness attainable within the limits set by the temperature and salinity of the water. With decreasing severity of climatic conditions,‡ the Barrier would then decrease both in vertical dimensions and in extent, until the present stage in its retrogression was reached.

* We have not sufficient information to say at what thickness of ice this large increase in velocity will become effective in preventing growth in thickness. To a very large extent it will depend on the salinity and temperature conditions of the underlying sea. It seems probable that this stage would be reached before the main body of the Barrier took ground and rested on the sea floor.

† Such Fast-Ice has been incorporated in the angle between the David and Reeves Glaciers at the junction of the Drygalski Ice-Tongue and the neighbouring sheet of Confluent-Ice.

‡ Not necessarily decreased temperature, but decreased difference between precipitation and denudation.

In the course of ages, if the present conditions continue, it will shrink more and more until only short disconnected floating Ice-Tongues remain jutting into the sea. Finally, these also will disappear, as soon as the alimentation on the Plateau becomes insufficient to enable the glaciers to reach the sea.

The possibility that growth may have taken place beneath the Barrier at one time in the past, requires fuller examination, as this possibility has been assumed by Debenham* in giving an explanation of the origin of the sponges, shells and mirabilite deposits found in McMurdo Sound and on the coast of South Victoria Land.

Growth due to heat conduction from the sea to the air, through an assemblage of ice crystals such as the Barrier, must be very slight indeed. Observations in McMurdo Sound on the growth of sea ice during the winter have, however, shown that the rate of growth does not decrease very greatly as the season advances and as the ice becomes thicker ; in fact, after the ice has attained a thickness of about 3 feet, its rate of increase remains sensibly unchanged. As pointed out in Chapter X, growth then proceeds for a time largely by deposition of the frazil ice crystals floating in the sea water below the under surface of the ice. The presence of these crystals may be looked on as an indication that the sea water is to all intents and purposes *super-cooled* and capable of forming ice on any obstruction it meets. It is clear that the crystals are present in greater amount near the upper surface, and that it is only the eddies caused by the sea currents which hinders them from rising to the surface. Deposition of frazil ice probably proceeds in the winter on the under surface of all ice masses in McMurdo Sound, but particularly where the ice is thinnest. The possibility of a net growth from below in the course of the whole year cannot therefore be neglected, and, certainly, such a process seems adequate to explain the occurrence on the surface of the ice of the deposits referred to.

Previous Extent of the Barrier.

Beyond the observation of Sir James Ross in 1841, we have no reliable evidence as to the previous extent of the Barrier, though there can be little doubt that a very large portion of the Ross Sea was at one time covered by a Barrier of the same type as the present one. At this period, the Koettlitz Glacier probably had a greater outflow of ice than the other valley glaciers on the western side of McMurdo Sound, but they must all have coalesced in a western portion of the Barrier. It follows that the Barrier movement along the coast of South Victoria Land was not predominantly from south to north. The presence of erratics of kenyte in the " Stranded Moraines " of McMurdo Sound and up to heights of 1600 feet in Dry Valley, New Harbour, has been adduced as a proof of the further extension of this ancestor of the Ross Barrier in the past. While ourselves believing in such a further northward extension, we are quite unable to admit that the presence of this material can be due to such a formation, for we cannot imagine circumstances of differential alimentation and ablation sufficient to account for the complete failure of the supply of ice from the Ferrar and Taylor Valleys

* F. Debenham, ' Quart. Journ. Geol. Soc.,' vol. 75, Part 2.

at a time when accumulation of ice elsewhere was so much greater. Local accumulation and movement from west to east must have served to push off the ice from the west coast. This opinion is strengthened by the fact that kenyte has been found by one of the writers actually in the moraines of the East Fork of the Ferrar Glacier, which are still surrounded by ice of local derivation. It is now known that local volcanic craters occur up the Taylor Valley. Those that have been examined are of basalt, but it is quite likely that kenyte also occurs. Further, as stated elsewhere in the memoir, there is definite proof that in the last ice-maximum the ice in the Ferrar was at least 2000 feet higher. Such a mass of ice pouring out to the east must certainly have deflected the stream from the Koettlitz, however powerful it may have been, far from the coast.*

It is probable that the Barrier did not, at its maximum, extend further north than the edge of the continental shelf, as the melting which would then have proceeded at the boundary of the Shelf-Ice would have been enormously greater, an almost inexhaustible supply of warm sea water laving its edge, strong currents, both vertical and horizontal, being set up as a result of the melting.

* It is, however, probable that the maximum activity of the Koettlitz Glacier was not coincident in time with the maximum activity of the valley glaciers, such as the Ferrar Glacier, leading directly down from the Plateau, but followed the maximum of the latter.

CHAPTER VII.

STRUCTURE OF GLACIERS.

Interest in the detailed structure of Antarctic glaciers must necessarily centre largely around the characteristics in which they differ from those of lower latitudes and of similar latitudes in the Northern Hemisphere. The glaciers examined by the present Expedition total some hundreds in number, but it is not intended to give a detailed description of any of these, with the exception of certain ice-formations typical of each of the main subdivisions of our classification which finds its most complete, or its only, manifestation in Antarctic regions (Chapter VI). The present chapter is devoted to a general discussion of the detailed macro-structure of Antarctic glaciers, with emphasis laid upon those points in which—for climatic or other reasons—the Antarctic glaciers, considered as a special class, differ from those of other regions.

The consideration of the glacier as a whole entails, of course, some reference to included or glacier-borne rock in the form of moraines of all types, and to the rock walls and bottom by which the ice mass is enclosed, and on which it rests. Whether, on physiographic grounds, we give greater credence to the claims of frost and thaw action, or to the planation carried out by the glacier itself, as the chief cause of the scooping out of the glacier valley, or whether, following the most conservative school of glacial physiographers, we look upon all glacier valleys as a modified inheritance from a pre-glacial topography, the glacier itself cannot be fully studied without some reference to the bed on which, and the walls between which, it lies. The explanation of the method of formation and modification of bed and walls can be left to the physiographer, but the effect of rock of all descriptions, in profoundly modifying the contour, the appearance and the structure of the ice in its neighbourhood, falls essentially within the sphere of the glaciologist.*

The detailed structure of an ice-sheet, whether a true ice-river, or an ice-formation of less determinate form, is intimately bound up with certain visible phenomena, which can be classified under headings for the more systematic grouping of the forces and processes of which they are the visible result. By the utilisation of such headings, the ordered study of ice structure is facilitated, and those selected for discussion here are arranged in the following table as nearly as possible in such order that there is a natural sequence in the processes which are their principal causes :—

(i) Moraines.
(ii) Siltbands.
(iii) Bluebands.
(iv) All other visible stratification (white banding).
(v) Pressure ridges and waves.
(vi) Crevasses.
(vii) Shear-cracks.
(viii) Form of glacier snout and wall of glacier.

* Methods of erosion by ice in the Antarctic will be discussed in the "Physiographical Memoirs of the Expedition."

(i) "Physiography: the McMurdo Sound—Granite Harbour Region," by Griffith Taylor.
(ii) "Physiography: the Robertson Bay and Terra Nova Bay Regions," by R. E. Priestley.

It is proposed first of all to discuss each section with special reference to Antarctic glaciers and other ice-formations in the South Victoria Land region. This having been done, the next step is naturally the comparison, so far as is possible, of the features characteristic of the Antarctic with those of glaciers of similar magnitude and type from the Arctic, sub-polar and temperate regions. The first portion of the chapter is thus based entirely upon the observation of the authors; the conclusions and comparisons of the second part are drawn mainly from the study of an exhaustive literature, and particularly of the excellent summaries which have from time to time been made by scientists recognised as authorities on this subject.

(i) Moraines.

Undoubtedly one of the most striking features of the Antarctic glaciers—not only in South Victoria Land, but also in other regions that have been discussed by the scientific staffs of expeditions—is the remarkable paucity of visible rock material either upon their surface, at their sides, or at their ends. This is an inclusive statement, which is modified only to a very slight extent by the variations observed along a stretch of coast such as that which, throughout a length of some thousand miles or more, has been carefully studied by British expeditions from 1901 to 1913. The majority of the largest ice masses are practically free from moraines. The smaller ice-formations of the type to which the name glacier was originally applied, lying between steep walls, and often heading in steeper amphitheatres, have, many of them, their own lateral and sometimes medial moraines. Both are, however, normally sporadic in occurrence, and are often represented on the surface by a few scattered blocks interspersed with more numerous " cryoconite " holes, and an occasional group composed of fragments all of the same origin, which bears witness to the disintegration of still larger boulders similar to those which have survived. Even where, owing to decrease of alimentation, excess of wind, or other factors, glaciers have shrunk and have left bare the lower portions of their valleys, the accumulation of moraine does not suggest there was a much greater amount in the immediate past.

The question at once arises:—Have the Antarctic glaciers ever performed much work of a rock-grinding and rock-transporting nature; and, if they have, where should we look for the fragmental material which should—judging by the evidences of more favoured countries—have been the ultimate result of such action?

In discussing visible moraine material, the greatest Antarctic ice-formations may be neglected. Shelf-Ice and Piedmont-Ice are alike, in that they contain little rock material, except in the form of silt and fine wind-borne detritus. Such moraines as exist do not persist long on the surface of ice-formations which essentially owe their survival and growth to an excess of precipitation over denudation. Moraines carried down with the ice of the most active glaciers which feed them do, occasionally, in favourable circumstances, remain on the surface for some miles out upon an Ice-Tongue or Shelf-Ice sheet. Rock material fresh-fallen from the cliffs at the base of such an ice sheet may afford some slight relief from the contemplation of an unchanging snow

surface. The persistence of such isolated moraines or rocks is, however, both unusual and ephemeral, and no typical moraines have been studied either upon Ice-Tongues, Shelf-Ice or Piedmont-Ice.

When we turn to true glaciers, however—the land ice formations grouped together in the classification under types II (*a*) and (*b*)—moraine material is found to play, if not a prominent, at any rate an important, part in the economy of the Antarctic glacier. It is true that " railroad " moraines are uncommon, but they do exist, as is shown quite clearly in Plate CXXXIV, which is a view of a moraine upon the Campbell-Priestley-Confluent-Ice. Plate CXXXV is a photograph of a lateral moraine of the Kœttlitz Glacier.

The normal type of Antarctic glacier moraine, as observed in the regions traversed in the researches of the British expeditions, is, however, better indicated in Plate CXXXVI.

In all three regions studied in detail by this Expedition, moraine material, though sparsely distributed, is universally present in valley glaciers. Four further examples of typical lateral and medial moraines are shown in Plates CXXXVII—CXL. It will be seen from a study of these seven photographs that, even on the Antarctic glacier, the amount of surface material is not negligible, though its occurrence and persistence at the surface is sporadic and ephemeral, in spite of a climate which one would not at first sight consider particularly favourable to the drowning or submerging of rock by ice.

The factor which must, we believe, more than any other, be directly responsible for the sparsity of original surface moraine material, and, indirectly, also for the shortness of its stay at the surface, is the large ratio of snow-covered to snow-free land. In the Antarctic regions, even in South Victoria Land, where the proportion of exposed rock is perhaps higher than in any other area of the continent, the amount of snow-free land is ridiculously small in comparison with that which is still swamped beneath the dwindling ice masses. In former times, at the date of the most recent maximum extension of the Continental-Ice, this disproportionality must have been still greater. That it is still the case in great degree to-day, can be seen from a scrutiny of the illustrations of the present memoir.

The bearing of this fact upon the amount of rock carried upon Antarctic glaciers is clear. Surface moraine may originate in two ways, according to modern glacial theory. (1) By accumulation from the rock walls and the amphitheatre in which the glacier heads, or from *nunatakker* or *nunakoller* surrounded by its ice; (2) by the upturning of englacial or subglacial rock material derived originally from points below the surface of the glacier. It should be stated at once, however, that, in the experience of the writers, there is only one single case, out of some dozens of moraines examined, in which the rock material must have been derived in the latter way.* Practically all the moraine material studied had undoubtedly fallen upon the glacier from the cliffs at some point further up its valley. In most places, when

* This case is referred to later in this chapter.

the moraine was followed upwards, the actual place of origin of the rock could not be in doubt.

The amount of surface-derived material is undoubtedly conditioned by the proportion of rock to snow- or ice-covered slopes (given similar conditions of alimentation and ablation at the sides or the head of the glacier). In the Antarctic, with its small amount of exposed rock, it is not to be expected that much will reach the surface of the glaciers, even when they abut against the slopes along which they flow. When, as is usually the case, they are bordered by steep radiation gullies only partially filled with rock *débris* provided by the "thaw-and-freeze" action along the exposed rock cliffs, the rock likely to reach their surface is reduced to a still smaller amount.

This is a factor of particular importance when the region—as is the case in the Koettlitz-Ferrar area along the west coast of McMurdo Sound—is one of extremely small precipitation, giving locally the nearest approach to polar desert conditions which has yet been met on the Antarctic Continent. Here, on the classical field of geological exploration in East Antarctica, the absence of surface moraines is unusually pronounced. Further south towards Black and White Island, and further north in the Terra Nova Bay district—where precipitation is greater and radiation gullies are less in evidence—although the proportion of rock to snow is, if anything, rather smaller, the amount of surface moraine is distinctly greater.

That the sparseness of surface moraine material is itself the principal cause of the shortness of the period during which it persists at the surface, can be best shown by analysis of moraines which have been closely studied. Wherever, as in the Ferrar Glacier, and, to a less extent, in the glaciers of the Cape Adare region, the blocks of the moraine are very scattered and the material small in amount, they usually disappear beneath the surface very quickly. If such a moraine is traced from the last projecting point at which it could obtain a fresh store of material, the isolated blocks of which it is composed can be seen to become gradually absorbed into the body of the glacier by the joint effect of two separate processes (Plate CXLI). The first and most important is the bodily sinking of the stone itself, due to its heating by radiation from the sun and sky. In general, a less effective, but locally an important, agent, is the formation of snow-drifts both on the weather side and in the lee of the blocks (Plate CXLII). These snow-drifts are then converted into ice in the normal way, the process being accelerated by radiation from the block against which they rest and also from the neighbouring blocks. The final result of these two processes is the production of an ice surface absolutely free from surface moraine material, but often markedly irregular owing to the presence of these "fossil" snow-drifts. This surface is pitted with numerous, roughly-cylindrical inclusions of nearly clear ice.

The difference between the two causes of the disappearance of isolated blocks is important—the latter is conditioned by local excess of precipitation over ablation; the former by marked excess of ablation over precipitation in the immediate vicinity of the rock. In general, the two processes are simultaneously in operation to the same

end—that of hiding the rock *débris* from view. Naturally, the former process alone operates in the burying of small individual stones and grains of sand.*

In any case, whatever the detail of their formation, such fossil moraines are the commonest form in which lateral and medial moraines are met in the lower portions of Antarctic glaciers where moraine material is not concentrated in important streams. When the latter is the case, however, as in the moraines shown in the photographs of Plates CXLIII and CXLIV, it will be seen that an entirely different action takes place. In both these examples, the medial moraine of the Dugdale-Murray Glacier and the moraine on the Campbell-Priestley-Confluent-Ice, north of Inexpressible Island, and in several other moraines with rock lying sufficiently closely together to act as a single large boulder, the effect of differential ablation is entirely different from the process just described as operating in the case of scattered rock material. The rock covering is here sufficiently dense to protect the ice beneath it both from the sun and from the wind. In the particular cases figured, the principal agent carrying out the denudation of the surrounding ice has been almost continuous wind which, by drift-chiselling and ablation—both inoperative upon the rock-protected ice beneath the moraine—have reduced the general surface of the glacier some 20 or 30, or even 50, feet below that of the ice underlying the moraine. As the ridge thus formed became more pronounced, the tendency of the rock to slide down became greater and greater until finally, in the case of the Dugdale moraine, the ice ridge beneath the moraine has now itself been exposed to the denuding influence of the wind. The result of further action will be to remove the ridge, and this effect will be hastened by the heating effect of the sun upon the dust-discoloured ice of the ridge.

In the meantime, where the moraine material has fallen, fresh ridges will arise. The illustrations form good examples of the way in which an even, thick carpet of rock will remain on the surface of a glacier for a considerable space of time, although scattered material is soon lost to sight beneath the ice.

An example on a smaller scale of the protective action of rock is afforded by single large rocks of considerable breadth. The "glacier tables" which result from the differential denudation of the ice underneath and around these large rocks are a feature of many Antarctic moraines of the type first described, and may often be the only surface survivals of an otherwise englacial moraine.

* If the temperature is high enough to permit a fairly free circulation of water in the upper layers of the glacier, the water produced around a small stone or a few grains of sand will run away, leaving a hole which may be bridged at different levels with thin sheets of transparent ice. If the temperature keeps too low for this to happen, or if the holes are refilled with surface thaw water, these "cryoconite" holes will be filled with beautifully clear ice, often with elongated air-tubes radiating from a central irregular air-space which clearly betrays the method of freezing by growth from the walls of the holes (Fig. 51). If, on the other hand, the holes become partially or wholly filled with snow-drift, and, as often happens, the snow-drift later becomes impregnated with water, the cryoconite hole will be filled with the curious radiating, roughly-prismatic ice aggregations, with the air-bubbles concentrated to form strong white lines between the crystals. This form has been well figured in the 'Memoirs of the Shackleton Expedition, 1907–9.'† Similar ice is commonly formed by the upgrowth of the ice crystals of fresh-water lakes into the snow-drifts above them.

† "Geology," Vol. 1, David and Priestley.

A typical example from the medial moraine of the Priestley Glacier is figured in Plate CXLV.

While the direct effect of the sun upon the rock material itself is perhaps the most general cause of the disappearance of surface rock material from the valley glaciers of South Victoria Land, the local effect of an excess of precipitation over ablation may bring about the same result. This has been especially the case in certain regions where the meteorological conditions differ to a marked extent from the desert wind-swept climate of the region considered as a whole. Marked exceptions to the general rule occur wherever a long stretch of unbroken cliff lies right across the path of the prevailing strong winds. This probably holds true whether the cliff face fronts the wind or interposes a true lee between the wind and the glacier. In such situations, surface moraines disappear for a time, sometimes to reappear further down the glacier, sometimes to remain englacial until they crop out at the face of the glacier cliff.

Thus, the intermittent surface moraine is a feature by no means unknown in South Victoria Land. Several cases have been seen and studied by parties of the present Expedition, and at least three different types respond best to different explanations. The simplest case is that first mentioned, where the moraine is temporarily swamped by the accumulation of snow on a stretch of glacier where alimentation is locally in excess of ablation and afterwards re-exposed in a region where denudation once more becomes paramount. Examples of such cases have been observed upon the west coast of Robertson Bay, but the best is to be seen along the northern edge of the Campbell-Priestley-Confluent-Ice, where the Corner and Priestley Glaciers and the Campbell Glacier add their quota to the great coastal sheet.* Here, the ridge of mountains, of which Mount Abbott forms the most prominent peak, forms a wind-break sufficient to ensure a permanent excess of deposition over denudation. The lateral moraines are swamped under this local accumulation of snow, but when they have moved further down the glacier the ice is once more exposed to the full fury of the gales which are characteristic of the autumn, winter and spring in this area. In a very short distance the accumulation of snow higher up the glacier is removed, and the moraines once more appear at the surface. The association of rocks in this and in the next case to be quoted, is fortunately such that no possible doubt can be entertained as to the correctness of the identification of the particular moraines.†

It is from the same region that the best example is drawn of the rejuvenation of a surface moraine which has disappeared from an entirely different cause, viz., the heating action of the sun's rays on the component rocks and the consequent sinking of the

* Map XIV.

† A moraine in which a white porphyritic granite and a red holocrystalline granite are associated with many normal schists and gneisses is paralleled by one characterised in particular by pyritic and graphitic schists. This, again, lies closely alongside two others, with a most interesting association of Beacon Sandstone with carboniferous markings and inclusions, and of ancient amygdaloidal volcanic rocks, quite unlike anything else that has been observed in this portion of the Antarctic. The merest neophyte in Geology could not but identify the rejuvenated surface moraines of the seaward portion of the Confluent-Ice with their originals proceeding from the Campbell, Corner, and Priestley Glaciers, respectively.

individual boulders. The western moraine of the Priestley Glacier is composed of scattered rocks, and very quickly disappears into the ice under the influence of a summer sun of great intensity, whose effect is increased by the radiant heat from numerous dark rock cliffs and by the direct action of thaw streams from the glacier. All trace of the rocks is lost two or three miles from their place or origin, and, though the snow-drifts caused by the Abbott Range pass over the hypothetical course of the submerged moraine, they are not directly responsible for its disappearance. Many miles to the south, beyond Inexpressible Island, where the ice of the Campbell-Priestley-Confluent-Ice coalesces with that from the Reeves Glacier and its derivative the Drygalski Ice Tongue, these moraines again crop out on the surface, the blocks being much more scattered and much more uniform in size, but still undoubtedly the same in origin. Both the seaward portion and the landward portion of these moraines were particularly carefully examined, as being the source of valuable fossil material, and there can be no doubt whatever that we have here a case, not of upturning of strata, but simply of excessive ablation, due largely to the gales which blow without intermission through some ten months of the year.

The Northern Party were held up for eight months in this vicinity, and, during the whole of this time, there was never a consecutive twenty-four hours free from wind of gale force.

In his studies of the Greenland glaciers, Professor Chamberlin has recognised for the first time, and given prominence to, the upturning of ice strata in a glacier as a source of surface moraine material. Evidences of such upthrust moraines were carefully searched for in the Antarctic, but only in two cases were moraines met which could conceivably be attributed to this cause. In one case, the irruption of a tributary glacier into the Sir George Newnes Glacier at the back of Robertson Bay was accompanied by marked upturning of the strata of the tributary. Along the junction of the two glaciers was an almost vertical plane of discoloured ice, and the upper surface of the plane was marked by an outcrop of a few stones and some grit on the surface of the Sir George Newnes Glacier. The moraine thus formed had no very visible origin at the sides of the glacier, and its presence is explained with more facility as due to the upthrusting of ground moraine at the point of junction with the tributary.

A second case, where the presumption might be that the origin of a surface moraine was sub-glacial, is that of the Hell's Gate moraine just north of Inexpressible Island. This might possibly be the result of the re-exposure of the surface moraine from Vegetation Island, buried and exposed again as detailed above; but the amount of rock in the moraine militates greatly against this theory, and it seems more likely that the rock is derived from some rock projection completely smothered in the ice-flood. Its arrival at the surface might then be due either to excess of ablation over deposition, to the upturning of layers of ice, or possibly to the former agency combined with growth of the ice-sheet from below, as explained by F. Debenham* in his paper on the origin of certain deposits of mirabilite and organic remains.

* "A New Method of Transportation by Ice," 'Q.J.G.S.,' vol. 75, part 2.

Although upturning of ice strata was observed in many glaciers, notably in the Shipley and Warning Glaciers, no other possible examples of moraines formed in this way were observed. All surface material examined close at hand was quite obviously derived directly from the cliffs bordering the glaciers, while other examples seen from a distance were so disposed that there is every reason to suppose that they also owed their origin to subaerial erosion and surface transport. The greatest accumulation of surface material occurred where it might be expected to appear, that is, at places where the glaciers pressed against their walls without the intervention of the radiation gully, which so frequently receives into its capacious hollow the results of the "frost-and-thaw" action which is undoubtedly the most potent factor of surface denudation in the Antarctic. In such places, where the radiation gully was non-existent, whether owing to the influx of an active tributary, to the accumulation of snowbanks which deflected falling rock fragments well out on to the glacier, or to the projection of a prominent bluff around which the glacier ground its way, greater accumulations of moraine than the normal were to be found. If the absence of the radiation gully was due to excessive accumulation of snow, the visible rock material was comparatively small, while the resultant shrouding of the rock slopes themselves in snow and ice also tended to reduce the aggregate of rock collected beneath the drifts on the glacier. In other situations, however, where the radiation gully was either eliminated or had overflowed with rock fragments, it sometimes happened that a very large accumulation of rock was observed. Such an accumulation—in an angle of the Priestley-Campbell-Confluent-Ice—is shown in Plate CXL. In such a favourable situation, all the phenomena so well described by Russell as occurring upon the moraines of the Malaspina Piedmont may be observed.*

It would sometimes be difficult to realise that the rock *débris* was ice-borne at all. Miniature hills and valleys, lakes varying in size from several hundred yards long to the smallest tarn, running streams, fossil lake bottoms covered with algæ and fungi, give to such a region a peculiar landscape of its own. It was not until the smaller details of the place were examined—solifluction cracks and crevasses, miniature ice-gorges conveying sub-glacial streams from lake to lake, *moulins* and occasional ice-dykes—that it became evident to the observer that the whole had its being upon the surface of the glacier, and that the rock covering responsible for the main features of the landscape was at most a few boulders thick.

Such moraines were not common, but the examples met deserve mention, as producing some of the most characteristic of the minor features of the scenery of polar glaciers.

The types of moraine most familiar to the recorders of the glaciology of other lands, and especially of the evidences of remote glacial periods—ground and terminal moraines—bulk so small among the visible evidences of Antarctic glaciation that their real importance is likely to be underestimated. The absence of striated boulders and of obviously ice-planed surfaces has been adduced as a proof that Antarctic glaciers

* J. C. Russell, 'Journ. Geol.,' vol. 1, 1893.

have done, and are doing, little work in comparison with other forces. With the suggestion that at the present time the Antarctic ice-mantle, considered as a whole, exercises a predominantly conservative influence, the writers are in accord. There are other evidences besides the absence of visible ground moraine which lead inevitably to this conclusion. Too much stress should not, however, in our opinion, be placed upon the absence of visible ground moraine and, in particular, of "rock flour," in support of this conclusion. It should be remembered that, owing to the configuration of the continent and the degree of intensity of its glacierisation, the natural habitat of the end of a vigorous Antarctic glacier is the sea. It is only very occasionally that active glaciers are found which, owing to peculiarly unfavourable alimentary conditions, do not reach to sea-level and push out well beyond the borders of the continent. It follows from this that the evidences of vigorous action shown by any glacier during the heyday of its life-cycle will be hidden from our sight beneath the sea. The South Victoria Land equivalent of the boulder-clay of, say, the Pleistocene glaciation of Europe, will not be pushed up upon the coast of a favourably-situated continental island, or even deposited upon broad lowland plains by swiftly-moving ice streams radiating from local sheets of Highland-Ice. The Antarctic continent is so formed, and the Antarctic climate is such that, at any time in its glacial cycle when the glaciers are moving rapidly outwards, either from the Continental-Ice of the hinterland or from the local Highland-Ice of the coastal ranges, the consequent ground moraine and rock flour will be spread out beneath the waters over the Continental Shelf. Until dredgings have shown that there is no great accumulation of such material upon the sub-oceanic borders of the continent, it is not permissible to argue that paucity of visible ground moraine indicates lack of efficiency of Antarctic glaciers. At present, what evidence we have rather points the other way. The only occasion upon which the Terra Nova's dredge was dropped off the Ross Barrier at the Bay of Whales, the haul consisted of two crinoids and several hundredweight of typical raw material for the formation of boulder-clay or perhaps a coarser till. Other dredgings have yielded similar, though perhaps less typical, material, while some of the best fossil specimens yet obtained from the Palæozoic rocks of Antarctica have been found in erratics thus dredged from the sea floor. Plates CXLVI and CXLVII are photographs of the terminal moraine of the Hobbs Glacier and a close view of water-sorted mud.

It might be argued that the exposure of such valleys as the Dry Valley of the Taylor Glacier* affords strong evidence that glacier action has not, even in the past, been very great. Here, terminal moraine can be studied, and it is certainly not of that type which might be expected if it had been formed during a period of great activity of the glacier. It should be remembered, however, that for some considerable time before the glacier finally commenced to recede, its movement must have been sluggish and its abrasive action slight. Most of the material left would be englacial or surface in origin, and, of this, such as has been exposed has been much shattered and altered in shape and appearance by the comparatively quick action of frost and sun. Though no rain

* The lower portion of the "Ferrar" Glacier of the maps of the 1901–7 expeditions. (See Map VII.)

falls, re-sorting by water is also not a negligible factor; and, even if evidence of abrasive action had originally been present, which is not likely, much of it would have been destroyed in the intervening centuries since the recession of the ice.

The study of englacial morainic material is of little interest beyond the immediate consideration of the effect of englacial boulders upon the structure of the ice around them. At a crevassed portion of any glacier, there may be a considerable transference of rock material from the englacial to the subglacial state, but, with these exceptions, the downward movement of such material through the ice is a very slow one under the influence of the greater specific gravity of the stone, and (in the upper layers) of the gradually lessening amount of heat energy received through direct radiation. The continual molecular movement which takes place in the flow of glacier ice involves a gradual downward movement of any heavier rock which it may be carrying. Normally, we should expect the boulders of a submerged surface moraine, for instance, to continue their downward course slowly but surely, and this expectation has been borne out on the few occasions when such a moraine has been observed to be intersected by the cliff face at the end of a glacier, or by the wall of a large crevasse. Boulders can then be seen dotted about much deeper in the glacier than they could have sunk as the consequence of the direct receipt of heat from the sun. Given a sufficiently stagnant body of ice and a sufficiently long period of time, the passage of a rock vertically from top to bottom of a body of ice is not only possible, but likely, though the presence of the greater amount of englacial material is probably accounted for more simply by its derivation from some submerged point of the rock walls or floor of the ice stream.

A curious feature of the ice immediately surrounding many englacial boulders is the conformation of the ice layers both above and below the boulder to agree roughly with the contours of the rock. In cases where such apposed structure is confined to the layers on a level with and above the rock, it is easy to trace their possible origin to an original snow-drift structure which has been perpetuated in the ice to which the original snow of the drift has been subsequently changed. The inception of a similar conformable structure beneath the boulder must be due to an adjustment of the underneath layers as movement takes place within the glacier. A gradual adjustment of the layers upon which the enclosed boulder rests might possibly be expected beneath such a rigid obstacle in the face of pressure applied from above.

(ii) Silt-Bands.

The consideration of moraine material, and particularly of englacial moraine, brings us naturally to the study of the bands of silt whose convolutions often form one of the most puzzling features of a glacier; while their presence may be at the same time of the most informative value in elucidating its past life-history. Almost all Antarctic valley glaciers are characterised by the presence of silt-bands, at any rate in their lower strata. On the other hand, the majority of ice-formations other than those allied to the true glacier are comparatively free from included grit and dust of any description.

There are two main sources which at once strike the observer endeavouring to account for glacial phenomena as likely to provide the silty material in these bands. The first, which probably accounts for the majority of the silt-bands occurring low down on the face of a glacier otherwise clear of rock *débris*, is the erosive action of the glacier on its bed. The second, which is responsible for practically the whole of the well-defined silt-bands of the upper strata of a glacier, is wind-borne dust derived from its sides, or from the walls of the cirque in which it may have its origin. The silt-bands formed in either way are, as a rule, indistinguishable from one another. Where a glacier is short and of steep descent, with abundant ice-falls, it is quite impossible to decide to which agency the bands owe their occurrence.

While the origin of the silt may be with certainty ascribed to one or other of these two causes—with perhaps locally the intervention of water—the actual mode of origin of the silt-bands in the particular position which they occupy is by no means such a simple matter, or capable of such a certain explanation. At least five methods by which silt-bands can be formed may be recognised, and certain occurrences cannot be explained satisfactorily even by the aid of all of these methods.

A study of the structure of the ice of the various Antarctic land-ice formations would not be complete without some mention of the many thousand bodies of Snowdrift-Ice which fringe the Antarctic coast, abut against every isolated cliff not actually bordered by a glacier or icefield of greater extent, and occupy every local depression in the wind-swept promontories and dry valleys which form the greater portion of the ice-free land of South Victoria Land. It is in these small bodies of ice that the silt-band is most conspicuous and assumes its most varied forms. It is in such small bodies that their occurrence is easiest of explanation, since the methods of formation and the modifications that can since have complicated the system of bands are few in number. Plates CXLVIII and CXLIX contain two photographed examples of such masses of Snowdrift-Ice showing well-marked silt-bands.

These bodies of Snowdrift-Ice are stagnant, and they are usually severely limited in extent by the circumstances of their environment. They cannot grow to a greater height than the projection which lies to windward of them. Further, if the lee is sufficient and the precipitation adequate, they pass over into other types of glaciers which for the present lie outside our sphere of consideration.

Almost invariably, the frontal cliffs of these "glacierets" are closely seamed with horizontal or sinuous bands in which there is a far greater concentration of fine rock detritus than in the intervening portions. Sometimes the number of silt-bands is very great; in other cases a few only occur. Their frequency is conditioned principally by the amount of annual snowfall; their thickness and their colour by the amount and character of the available rock material.

This is especially well seen along the two sides of the coast of Robertson Bay. To the east, the bay is bordered by the steep multi-coloured slopes of the volcanic complex of Cape Adare, from the heights of which frequent gales of great fury sweep down all the finer products of the frost-weathering which goes on uninterruptedly throughout

the year. To the west, calm weather with light airs is the rule along a coast where the only sources of rock are the relatively few bluffs of green, comparatively resistant quartzites and slates. The eastern coast of the bay is accordingly lined with deep discoloured drifts, with frequent bands of black, red, brown or yellow silt, according as the material composing the fragments is predominantly basalt, basaltic scoria, or varieties of tuff. To the west, the snow-drifts are conspicuously cleaner, and the discoloured bands are further apart. Such as do exist are filled with rather coarse fragments of the quartzite and slate, both of these rocks tending to cleave into sharp-edged fragments of rhomboidal shape rather than to crumble into dust.

The cause of the silt-bands in such drifts is self-evident when studied in so favourable a spot, especially when, to the evidence provided by the rocks, is added that afforded frequently by the inclusion of penguin feathers, of wind-blown fragments of seaweed from raised beaches, or more infrequently of fragments of moss. The life-history of the drifts is clear. They are screes of mingled rock fragments, snow, snow-drift and wind-driven rock dust. The darker bands of coarser material represent the outcome of the summer months, when the snow battles least successfully with the accumulation of the heavier fragments loosened by the thaw and by the frost from the cliffs above. Less well-defined bands arise from concentration due to the occurrence of prolonged periods of ablation between the incidence of snow-carrying winds, but these latter must often be telescoped into each other during the succeeding summer season. In the smaller masses of Snowdrift-Ice, this is probably the only method by which such alternation of silt-free and silt-impregnated ice can arise. In the larger examples, where the Snowdrift-Ice passes gradually into Cwm-Ice, or into a baby glacier, other complications will arise which will be referred to later.

The normal contour of these silt-bands, in the simplest imaginable case, will be that of the upper surface of the drift which forms the top of the ice-body. This may, of course, vary according to the situation and environment of the drift, or the shape of the hollow in which it lies. The contour will, however, be of simple shape in the majority of cases, and the silt-bands will then show up at the vertical face of the ice-sheet as horizontal, or gently undulating, but somewhat discontinuous lines, as shown in the illustrations of Plate CXLIX.

It is hardly necessary to point out, however, to any reader with a personal acquaintance with the effects of wind or thaw sculpture upon snow or ice surfaces, that the simple form thus indicated may be departed from to a very considerable extent. A study of possibilities in this respect would convince the observer that practically any of the many diverse folds which appear in the strata of Snowdrift-Ice may be explained in this fashion. A particularly interesting example showing silt-bands apparently crossing one another is shown in Plate CL.

The most markedly unconformable surfaces may be expected, and are indeed observed, and much apparent folding, with the possible exception of certain symmetrical overfolds which will be referred to later, is susceptible of explanation without consideration of movement within the body of the ice. From the nature of the ice masses

we are at present considering, movement other than molecular readjustment is not likely to occur; certainly movement sufficient to produce folding is unthinkable. Yet it is in these masses that some of the most sinuous silt-bands are seen—appearances which would undoubtedly have led to the assumption of movement of the ice on a large scale, had they been found in ice-sheets of a size and in a position where movement might naturally be expected.

A particular type of unconformity which owes its origin to a similar sequence of events is figured in Plate CLI. Here ablation or ice-movement has caused the formation of large hollows in the surface of a glacier, and, in the particular illustration, one such hollow, partially filled with fresh deposits of horizontally stratified snow, has been exposed in the glacier cliff. In the case in question, the cause of the phenomenon is easily seen, and the recent life-history of the snow and ice in question is easily deciphered. It can, however, be imagined that should such an occurrence take place comparatively far back in a glacier, so that the snow layer was completely changed to ice (as is the case in Plate CLII), and had, moreover, been covered by ice-strata of less local occurrence (as in the series shown in Plate CLIII), the elucidation of the cause would not be so easy, and the explanation would perhaps be more open to controversy. Further, should the lower and upper strata be thrown into contortion by ice-movements on a large scale, a confusion of banding might result which would altogether defy detailed explanation.

A further complication, which may arise in a similar manner, is shown in the photograph in Plate CLIV. Here, two unconformities occur one above the other. Given an alternation of periods in which precipitation and ablation, respectively, preponderate (or even changes of wind direction resulting in the alternative formation and destruction of an efficient lee), there is no limit to the number of such discontinuities which may occur in the same glacier. In some cases, such unconformities have been rendered more evident by the occurrence of two separate systems of crevasses, one confined to the lower layers only, the other common to both. Such a case occurred in a berg near Butter Point in McMurdo Sound, and is shown diagrammatically in Fig. 89. The comparatively common occurrence of bergs of the type figured in Plate CLV proves that the occurrence described is fairly frequent in the life-history of an Antarctic glacier. The same action goes on during every strong wind on the surface of every snow-covered mass of ice, though on an infinitely smaller scale which may not be preserved as a detail of the major stratification of the ice-sheet.

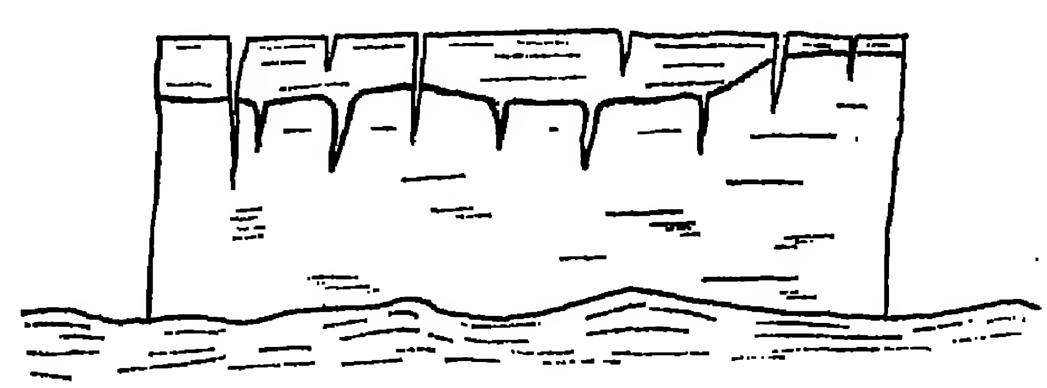


Fig. 89.—Iceberg with unconformity and two series of crevasses of different ages.

An interesting feature of such unconformities is the persistence of the appearance throughout long periods of time, the unconformities being still well defined and recognisable even after the ice above and below the lines, when examined in detail, appears to have much the same granulation and much the same air-content.

In many cases—in fact, in the majority of cases—the unconformity is rendered more apparent by the concentration of wind-blown dust along the plane of discontinuity, so that the latter is often itself a silt-band having an origin, similar in everything but magnitude, to those already described as causing the characteristic horizontal banding of masses of Snowdrift-Ice.

A second method by which silt-bands in ice have been formed in Antarctic glaciers is by the inclusion of dust and other detritus in open crevasses. Normally, the crevasses in the larger glaciers that have been studied in Victoria Land are snow-covered for the greater portion of their existence, so that this method of production of silt-bands cannot occur to any great extent. In the steeper ice-falls, however, this is often not the case, and there seems little doubt that, in this manner, some of the most complicated systems, of all those that have been observed, have been formed.

Such a formation is seen along a portion of the frontal cliff of Warning Glacier, one of the small glaciers heading in cwms on Cape Adare and falling steeply down some two or three thousand feet into the sea below.

The whole length of the glacier is just over one mile, and its gathering ground is so small and local that it can never have been supplied with sufficient snow to cause a very rapid movement. At the present time, it is practically stationary, yet the ice cliff which fringes the glacier along its whole seaward face shows sections where the ice is seamed with silt-bands folded and brecciated into the most complicated shapes, as if the ice had been hurled against some obstacle which had crushed it out of all semblance of its original self.

Above the tongues of the glacier and the overhanging fringe which connects them, where the ice no longer reaches sea level, are a series of magnificent ice-falls, the crevasses of which are open to the winds, and into which must be blown immense quantities of dust particles. It seems certain that the confused *mélange* of silt-bands and brecciated blocks of discoloured ice is caused entirely by the passage of the ice of the glacier over these falls, the result being a breccia which gives the impression that the ice has been exposed to irresistible pressure, rather than to the tensions which have caused the crevasses to which the structure is due.

The question has been raised by members of the Expedition whether most, if not all, of the silt-bands which crowd the lower strata of the valley glacier may not be due to the inclusion of dust in the major crevasses of the glacier. It has been argued that the more rapid movement of the upper layers of ice will gradually cause the change of these crevasses from vertical to approximately horizontal, with a slight uptilt towards the lower end of the glacier, which would satisfactorily explain the tendency to upturning of the silt-bands which has so frequently been recorded. The small vertical distance between the bands is explained by the upholders of this hypothesis as due to the thinning out of the layers of dust-free ice between individual crevasses, which would be brought about by the difference in velocity of movement between the base and the top of the glacier. While admitting the adequacy of this as a common method of formation, the writers cannot accept it as a complete explanation of the occurrence of

the bands. The explanation of the closeness of the bands to each other (vertically) seems adequate, but the majority of the crevasses of the glaciers studied are, with few exceptions, far too irregular and discontinuous to give rise to the often orderly sequence of silt-bands observed.

There remains the accepted explanation of the derivation of silt in the lower strata of a glacier—its collection by the glacier from the more prominent of the obstacles over and around which its course is directed, or from its bed and its subglacial moraine. The weight of evidence in favour of this method of derivation for the greater quantity of the rock material in a glacier is undoubted, but little direct support can be adduced from the study of glaciers in the South Victoria Land region. It seems the most competent explanation of the occurrence of the *débris*, but the sorting of the material thus gathered into definite silt-bands does not so easily fall into line. The passage of the ice of the glacier over bars set transversely to its course, such as are likely to arise owing to unevenness in the hardness of the rocks composing its bottom, might be competent to explain the banding in some measure. Even this, however, does not seem adequate to account for their regularity and universal occurrence. A photograph of the root of Warning Glacier, where the ice has broken back far enough to expose the outline of a rock bluff over which it passes, does suggest that the *débris* in the lower portion of a glacier will be roughly disposed in surfaces parallel to the outline of the bed (Plate CLVI).* The explanation of the occurrence shown in the photograph does not at once suggest itself, however, unless, as seems possible, the ice portrayed is part of the original Snowdrift-Ice, which was the ancestor of, or was flooded by, Warning Glacier, so that the silt-bands are simply concentration bands such as have been described earlier in the chapter.

The regular disposition (in bands) of rock plucked from the bottom and the submerged portion of the walls of a glacier valley does not seem likely to be original, and the explanation of the arrangement as a secondary re-sorting is difficult of explanation. That this is, however, the most likely explanation for the presence of the *débris* in the lower layers must be admitted. That rock material thus carried may, in time, even reach the surface of the glacier, has been proved by Chamberlin's researches in Greenland. From the Antarctic, confirmation is afforded, both by the not infrequent occurrence of upthrust in Antarctic glaciers and by the occasional appearance of mysterious surface moraines, without any very obvious surface derivation.†

* The attitude of the figure in this and many other ice photographs is explained by the difficulty of using pen or pencil at very low temperatures. The Warning Glacier photographs were taken during spring sledging, and identification was much aided by the use of the semaphore alphabet.

† An alternative explanation of the latter is afforded by the theory put forward by F. Debenham, which is the only satisfactory explanation yet suggested to account for the sporadic occurrence of mirabilite deposits and organic material on the surface of glaciers floating over enclosed arms of the sea. By this theory, the morainic material would be derived from the sea bottom, and have finally reached its present position through a combination of growth from below and denudation from above. In this connection it is interesting to note, that the most probable instance recorded from the regions examined by the present Expedition was the one from north of Inexpressible Island, which was, in fact, associated with one of the shell deposits to which Debenham's theory more particularly refers.

Besides the horizontal silt-bands which play so important a part in rendering visible the smaller details of glacier structure, there occur frequently, scattered here and there along the face of a glacier, much more irregular bands, few in number, irregular in disposition, and much more vertical in alignment. These may, according to the experience of the writers, be correlated with the carriage of rock *débris* from higher to lower strata of the glacier, either through the medium of partially-filled crevasses, or of channels excavated in the ice by streams. They are decidedly minor features, but are interesting as affording the true explanation for many of the irregular or vertical bands of discoloured ice seen in the faces of bergs, and difficult to account for, unless viewed in relation to the glaciers from which the bergs have their origin.

(iii) Blue-Bands in Ice.

The stratification of the ice of an Antarctic glacier is rendered visible even from a great distance if silt-bands are present and well defined. A closer examination of the face of almost any glacier, however, whether it bears an appreciable amount of silt or not, will show that its whole mass is composed of an alternation of strata which are more or less easily distinguishable, either by the amount or by the mode of arrangement of their included air-bubbles. The universality of this stratification and the great number of the layers which comprise it, are perhaps the most striking criteria of the climatic conditions under which Antarctic glaciers have been formed, as opposed to those of more genial climates. The temperature of the Antarctic summer is such that, but for the influence of the wind, every fall of snow of any magnitude would add its quota to the glaciers and icefields on which it falls. The only exceptions, and exceptions that might be expected, are for small rock-bound ice masses, and those which—for example, the Ferrar Glacier—are enclosed in rock valleys unusually deep in proportion to their breadth. In such cases, re-radiation from rocks and the heating of bodies of stagnant air do occasionally lead to thaw on a comparatively large scale, as on one occasion, in 1908, on the Ferrar Glacier, when the air temperature ranged between 34° F. and 40° F. for nearly forty-eight hours. In all normal cases, however, this action does not take place.

Were it not for the prevalence of strong gales which, by their accompanying drift snow and by their ablative action, drastically modify both the distribution and the persistence of the snow which falls, the stratification of the Antarctic glaciers would be a still truer record of the precipitation than is the case. As it is, the record is too complicated to afford much reliable evidence of individual past snowfalls, though, in isolated cases, evidence has been obtained by trenching which agrees very well with the weather of the particular season.

It is to such trenching and to the evidence afforded by the observation of the walls of crevasses, that we must look for an explanation of various anomalies in the stratification of Antarctic glaciers, as observed in their end faces and side-walls, which are at first sight not altogether easy of explanation.

After the silt-bands which have already been considered, the most conspicuous phenomena of the stratification are the air-free layers which occur as more or less brilliant blue-bands, irregularly spaced through the thickness of most glaciers. These vary in alignment from vertical to horizontal (being mostly approximate either to one or the other direction), and in thickness from many feet to a fraction of an inch. They may be divided into at least three classes, and it is under these headings that it is proposed to consider them in some detail and to endeavour to account for their formation on theories based, so far as possible, on direct observation.

(a) *Vertical Ice-Dykes.*—Perhaps the most striking and frequent (especially in the northern regions of South Victoria Land) of all the types of blue and white banding are the vertical, or nearly vertical, ice-dykes which obviously bear little relation to the horizontal stratification of the glacier.

There is fortunately no doubt about the origin of this striking feature of the Antarctic glaciers, for every stage may be seen from the open crevasse to the perfect blue ice-dyke, with the air concentrated in regularly-arranged air-tubes which do not appreciably affect the brilliant blue colour of the ice. The occurrence of these ice-dykes is particularly frequent in glaciers, such as Warning Glacier, which descend steeply from a high elevation, and are in consequence particularly heavily crevassed. Their formation is favoured when, as in the same instance, the summer climate is comparatively warm and snow-free, so that the crevasses of the icefalls often lie open throughout the summer when the influence of the summer sun is at a maximum. The examples figured in Plates CLVII and CLVIII are taken from this glacier, but are typical of the bands wherever they occur. Plate XCV shows a similar ice-dyke taken sufficiently close to bring out the detailed arrangement of the air-tubes.

They are very common in all glaciers which are much crevassed, but comparatively stagnant. For their greatest development, the ideal conditions are the presence of numerous crevasses which remain open for a considerable time and are acted upon by a rather intense sun in the summer.

The original method of formation of the ice in the more perfect of the blue dykes is betrayed by the regular arrangement of the air-content in the form of long tubes, often of hexagonal cross-section, lying perpendicular to the sides of the crevasse. The growth of prisms outwards from the walls of crevasses, which has been observed in rather wet crevasses in the summer, is doubtless the first stage in such a process, which is much hastened by the presence of abundant water. That this is the method of formation is also suggested by the fact that, in the case of imperfectly-filled crevasses, little geodes filled with snow and air have contained rather imperfect crystal faces of the constituent crystals which formed their walls.

The curved arrangement of the tubes in Plate CLIX shows that the method of formation of the dykes is not always so simple as that just described, but it is the opinion of the writers that, in all cases where such tubes were formed, the method of formation of the ice has been through the formation of crystals whose length greatly exceeds their breadth. A good analogy is afforded by the occurrence of similar radially-

arranged air-tubes in certain cryoconite holes, where the fresh ice filling the holes has been formed from pure water uncontaminated with snow. Excellent examples, one of which is shown in Fig. 51, Chapter III, were seen in the Dugdale-Murray medial moraine to the south of Robertson Bay, but all attempts to pick them out to be photographed were failures.

The above sequence of events results in the formation of the pure blue ice-dyke, which is the most perfect form of a phenomenon which can be seen in all its gradations down to the open crevasse. Many were seen which, while partially filled with blue ice, also contained a fair quantity of less pure ice which had been formed by the precipitation of snow masses with included air into the thaw-water filling the bottoms of the crevasses.

Much more common still were heterogeneous masses formed of a medley of irregular blocks of glacier ice and ice formed from snow *débris*, while wind-blown dust was common. Cases were also seen of the inclusion in such ice-dykes of solid blocks of névé, or normal glacier ice formed from nèvé, which was the result of the freezing of a snow-lid in place. In such a way, the form of the snow-lid was well preserved, though unfortunately no section was seen perfect enough to photograph well. Large masses of the curious aggregates of pure ice crystals bounded by white air-laden lines were also seen. Here, again, the formation was clearly due to the impregnation of snow by water and a consequent very perfect recrystallisation which had resulted in the concentration of almost all the air in the snowy boundaries between the crystals. In some cases, this type of ice had weathered most markedly, the snowy ice between the crystals having disappeared entirely, leaving the individual prisms standing up like radiating columns.

(*b*) *Horizontal Blue-Bands.*—The second type of blue-band, much more an integral portion of the glacier and much more important to the elucidation of its life-history, is the horizontal band. These are often persistent for great distances, but more usually are disposed in the form of thin long-drawn-out lenticules.

It is unfortunate that the photographs taken of these horizontal bands were not so successful as those of the ice-dykes, but examples are shown in Plates CLX and CLXI, where they can be made out quite clearly as dark lines running along the face of the glacier.

Bands of this kind, which are common to almost all Antarctic ice-sheets (though in many cases they may be obscured by subsequent changes), were best seen in, and are figured from, the glaciers on the western side of Robertson Bay. Perhaps the best example of such a normal blue-band was that occurring in the Shipley Glacier, north of Cape Barrow, where a narrow band, nowhere more than a foot thick and slightly irregular both above and below (though more so below than above), extended along the face of the cliff for about half a mile before dying out as if it were a section of a very slightly-curved lenticule. The majority of the pure blue horizontal bands on this and other glaciers were, however, much less persistent and much thinner, ranging in thickness from less than ½ inch to 2 or 3 inches, and in length from a few yards upwards.

One method of formation of such bands is described when, in Chapter III, mention is made of the inception of an ice-crust some few inches above the surface of melting sea ice in McMurdo Sound and Robertson Bay. In this case, the conditions were peculiar, and the presence of the warm sea ice below hastened the formation of the crust at the expense of the snow beneath it, until the latter entirely disappeared, leaving a thin " pane " of ice suspended at its edges from the more solid snow-drifts around it. Similar exaggerated cases were frequently observed in the height of summer on the surface of glaciers which were so situated that radiation could exert its maximum effect. Though no suitable transition cases were seen for some time, it seemed probable that the formation of some of the blue-bands in many glaciers must be the result of some such process.

During the course of a sledge journey in the Terra Nova Bay district, in the summer of 1911–12, undoubted proof of this method of formation of blue-bands, precisely like those formed in the normal life of a glacier, was obtained. The first examples were seen at the surface of the snow of a local gathering ground, or névé-field, in the lee of the Northern Foothills bordering the Campbell-Priestley Confluent-Ice. Here the drifts were many of them covered by a thin glass-like crust, which was underlain by a coarse granular snow which was only slightly coherent, and which had easily been removed by the action of wind and drift, leaving (Fig. 24, Chapter I) overlapping edges of knife-like sharpness, often extending some 9 inches or 1 foot beyond the low snow-wall on which they were supported. The strong sun of the few previous days had formed the crust by deposition of vapour rising from the upper few inches of snow. As always happens in such cases, the smaller snow-grains had disappeared and the larger ones had grown at their expense, giving a coarsely granular texture to the snow-drift. The excess vapour had solidified on coming into contact with the current of cold air passing slowly over the surface of the glacier, which was the nearest to a calm experienced in this particular region. It was curious that only certain snow-drifts had been markedly affected by this process. The later-formed ones had not yet consolidated, and were composed of larger grains without a crust; the snow-drifts of the previous winter, which had a very compact texture, had been modified to a much less extent. In this single region, the summer weather was actually producing the three or four different types of ice which are characteristic of the normal Antarctic glacier. It was only necessary to imagine the subsequent exaggeration of the initial differences of texture thus produced to understand quite clearly the appearance of such a tract as it would possibly appear, hundreds of years later, at the terminal face of the glacier.

That the process does continue, even when the surface has become covered by additional layers of snow, so that it is no longer exposed to the direct action of the sun, was amply proved by observations made a few days later in a locality farther up the Campbell Glacier. After passing over a strip of blue ice glazed by the sun and modified to a depth of many inches, another considerable area covered with thick snowdrifts was encountered.

Here, in the course of digging out snow-blocks for the tent, such an interesting section was exposed that the operation of trenching was repeated in several places. Plate XXIV

Q

illustrates the face of one such excavation; Plate CIV is a view of a sample of the large-grained snow beneath the upper crust. Snow had recently fallen and was lying loosely on the ground to a depth of 9 inches. Beneath this was a light, but thick, crust of névé which itself covered some 3 to 6 inches of granular snow. The next layer was the most important one for the elucidation of the method of formation of the blue-bands. It consisted of a sheet of pure ice, varying from ¼ inch to 2 inches in thickness and was evidently the result of the continuation of the process which has already been described. Underneath it for at least 18 inches there was nothing but loosely coherent grains formed from particles of snow and ranging individually up to ⅛ inch in diameter. The majority were quite separated, but here and there were a few joined together to form a miniature lump of true Antarctic névé (see Plate CV, Chapter III). Given still more accumulation above, with sufficient pressure to close up the greater portion of the space left by the extraction of water vapour, and the result would be just the type of section shown, somewhat poorly, in the photographs of Plates CLX and CLXI. The most interesting thing about the formation of these local blue-bands is that, during the whole time of formation, the temperature of the air had never been within several degrees of the freezing-point. It is possible that the temporary formation of water might have taken place during the initiation of the crust on the surface, but it certainly could not have been present during the subsequent modification resulting in the thickening of the ice-crust below the freshly-fallen snow. The snow was singularly free from included rock-dust, and the process appeared in every way to be the normal one through which the majority of the glacier ice formed, at any rate at low altitudes, in this portion of the Antarctic, has its origin. This process is adequate to explain the general appearance of the thinner and more local blue-bands seen at the terminal faces of the glaciers of the Robertson Bay and Terra Nova Bay region. Further to the south, the main difference in the glacier faces examined lay in the comparative freedom from these bands of pure blue ice, except in conditions exceptionally favourable to the action of the summer sun.

The stratification in the ice of many of the glaciers of the Ross Island area and also of the huge masses such as the Ross Ice Barrier, the Drygalski Ice-Tongue, etc., was mainly confined to alternations of whitish ice with more air-bubbles and bluish-white ice with fewer air-bubbles, to which we have given the term white-banding, to distinguish it from the stratification at present under discussion. The origin of these, though touched upon in foregoing paragraphs, will be more fully discussed later in the chapter.

The absence of the blue-bands in these latter ice-formations is undoubtedly to be correlated with a greater severity of summer climate in the regions where they exist. The farther south one goes, the less the altitude of the mid-day sun and the less the insolation. A similar result is attained at a lower latitude, through the entire absence of rock and sea as conservers and re-radiators of the sun's rays. Thus, as might be expected, it is found that, while in lower latitudes the formation of blue-bands of the type described above proceeds normally in all ice-formations, in slightly higher latitudes

it proceeds normally only in the smaller rock-bound glaciers and snow-drifts and along the margins of the greater icefields where their rock walls produce a marked effect. In the highest latitudes of all, as for instance on the plateau about the South Pole, one would expect to find an absence of crust (other than wind crust) which would be directly correlated with low summer temperatures and low altitude of the sun. That this is the fact is borne out by the discovery of deep uncrusted surfaces on the polar journey.

While the normal thin horizontal blue-banding in the Antarctic glacier of the lower latitudes is elucidated by the actual processes taking place at the present time in surface snow-drifts, the more persistent and thicker bands occasionally found at one or more levels in a glacier face cannot be accounted for in this way. We refer, for instance, to the band occurring half-way down the face of the Shipley Glacier, which extends for at least half a mile and is a foot or more thick, while horizontal bands of much greater thickness have been recorded from other glaciers.

One thing seems undoubted, namely, that any adequate hypothesis put forward to explain such an occurrence must take into consideration the action of water, in some cases of a considerable body of water, which alone could account for such thorough recrystallisation as is implied by the complete disappearance of air from bands of glacier ice of considerable extent and often many feet in thickness. At least three processes have been actually observed which are sufficient to account for a great number of such bands, and, indeed, which must from their very nature give rise to broad and deep bands of blue ice in the body of Antarctic glaciers.

The establishment of meteorological cycles in many countries whose climate has been under systematic observation for considerable periods of time, brings into prominence the idea that, in the Antarctic also, where, unfortunately, we have no long-continued series of observations, there quite probably occur periods during one portion of which the climatic conditions are more favourable to the precipitation and preservation of snow than at other times. Certainly, we know from the observations we have been able to secure, that the snowfall and wind velocity—the two factors upon which the accumulation of snow in any particular district depends—vary from year to year.

Also we know that, while at one portion of its course a glacier may be exposed to continual blasts of wind which keep it swept clear of snow, at another portion its surface may be in such a position that the region is predominantly one of accumulation. At the same time, it should be borne in mind that the great majority of the larger Antarctic glaciers are moving, albeit slowly, so that the surface exposed for some years to the polishing blasts of the wind and, incidentally, also, to the thawing effect of the sun, will sooner or later pass beneath the protective covering of snow-drifts, and that under this covering the aspect imprinted upon it by the vicissitudes through which it has passed higher up the valley will be preserved.

A closer consideration of these varying factors will disclose many combinations which will tend to preserve névé as névé, or at least to modify it only very slowly into a whitish bubbly ice; while, on the other hand, other combinations of circumstances will

tend to hasten the change in certain portions of the ice mass, and may produce as a final result the blue-bands for whose presence we are endeavouring to account.

Let us, for example, take the case of a glacier where a stretch of some 2 or 3 miles is so exposed to the wind and the sun that the net result of their efforts is an excess of ablation over deposition. The resultant surface of the glacier will be of blue ice. This has been proved again and again in the many glaciers traversed in South Victoria Land. In the summer, this stretch of blue ice may be exposed on occasion to a temperature above freezing-point. On one occasion, on the Ferrar Glacier, one of the writers was a member of a party which was obliged to pull for four or five hours beyond the limit of a normal day's march before a single snow-drift or dry patch was met suitable for a camp-site. The whole surface of the glacier was covered with a network of streams only a few inches deep, but covering half the surface of the ice. This was an exceptional case, but on that occasion the top ice of the glacier must have become completely waterlogged to a depth measured in feet. The constant seeping upwards of the air contained in the ice could be seen and heard by the bursting of the air bubbles as they reached the surface. In 48 hours the thaw had ceased, but who can doubt that the result, even in this short period, was the formation on the surface of a band of pure, practically air-free, blue ice which must have been of considerable thickness. Given favourable circumstances during the succeeding winter, or the passage of that ice behind a projection where snow was liable to accumulate throughout the year (as actually happened a mile further down the Ferrar), and the band in question would finally appear at the terminal face of the glacier precisely as did the band in the Shipley Glacier and other similar bands which have been seen elsewhere.

The intervention of an extreme thaw, such as that referred to, is not necessary for the formation of quite thick blue-bands, for many of the Antarctic glaciers are very stagnant, moving only a few feet a month, while the conditions in their valleys may be such that for stretches 2 or 3 miles in length, ablation and wind-action keep a clear ice-surface practically throughout the year.

In such cases, time will do as much to produce considerable change as was accomplished by more intense thaw conditions in a few hours. Though ablation may lower the surface a few inches each year, the limit of action will still be set by the limit of effective work of the sun's rays and of the water produced by thaw. When the bare surface finally disappears, as it practically always does, beneath the snow-drifts accumulated in the opening of the glacier valley and along the coast on which it debouches, the growth of the blue-band will almost or quite cease. When the old surface reaches the terminal face, however, it will appear as a broad blue-band, slightly irregular, but still very definite and very marked, amongst the less well-defined strata of normal glacier ice.

That such action is commonly producing blue-bands may be seen from a study of the unconformities already referred to in connection with the study of silt-bands due to concentration. The ice immediately below such unconformities is invariably freer from air and consequently bluer than that above.

Here, again, the formation of the major horizontal blue bands will go on more freely, the more genial the climate. The extreme case is seen in the blue ice of the glaciers of temperate climates, but differences can be seen quite clearly in different latitudes of the Antarctic itself.

Finally, some remark must be made of various ways—all of them connected with the short Antarctic thaw season—in which local bands and bodies of blue ice, sometimes of considerable extent, but on the whole of irregular shape, may be formed. Several quite different methods of formation have been observed, each of which may account for some tracts of blue ice. The principal ones worthy of particular notice are as follows.

The surface of the normal glacier of any length is by no means regular, even if we except the ice-falls and structures etched by thaw or wind, or due to the local occurrence of rock material. One of the principal differences between the work of large bodies of ice and of water is that, while the latter tends to grade its bed, the former does not do so to nearly the same extent. In fact, it is possible that, when a glacier has taken over a graded river valley, it may accentuate such small irregularities due to different hardness of rock as may already be present. In accordance with this, we may expect to have the ice dammed back to some extent in passing over or round such obstructions, with a tendency to flow uphill on the upper side of the obstacle. That this actually happens will be a fact within the common knowledge of all observers of glaciers on a large scale. By this means, large shallow basins are formed on the glacier surface, while the local accumulation of drifts in favourable situations, and the conversion of their lower layers into ice, affords another notable cause of the formation of similar basin-shaped irregularities.

In temperate climates, where the general air temperature is sufficient to ensure the action of thaw-water comparatively deep in the bowels of the glacier, it is not usual to find supraglacial lakes of more than a strictly temporary nature. In the polar regions, however, and especially on the Antarctic Continent, such phenomena do occur with fair frequency. The writers have sometimes been members of sledge parties which have been seriously incommoded by the intervention of such lakes across the path they were following up or down a glacier. Even the formation of cracks and crevasses does not readily drain supraglacial lakes in Polar regions, for anything but a big crevasse is quickly choked with newly-formed ice before much water can drain away. These supraglacial lakes seldom tend to form in places where movement on a large scale is likely to take place, but are commonly met on relatively stagnant glaciers, such as the majority of the glaciers of South Victoria Land. They occur usually on the gentler slopes and, particularly, where valley glaciers debouch on to an ice-plain such as a sheet of Confluent-Ice, Piedmont-Ice or an Ice-Tongue. Intermittently—when periods of thaw set in—they are fed by the glacier streams, but in the intervals they are choked with snow and quickly cemented into a dull greenish-coloured ice; or, if snow does not fall upon or drift into them, they freeze into plano-convex lenticules of blue ice which would show up very distinctly when dissected in a cliff face. On one occasion, when one of the writers

was sledging on the Ferrar Glacier, an excellent view was obtained in the sides of a crevasse of two or three lenticules of blue ice which must have been formed in this way. This was rendered more probable in that, in this very region, a similar lake of slush had compelled the party to make a considerable detour on the previous day. Such lakes have also been met on the Campbell Glacier, at the point where the Priestley Glacier debouches into the Campbell-Priestley Confluent-Ice, on the Murray Glacier in Robertson Bay, and, on a smaller scale, on several smaller glaciers. They are quite different in origin from the majority of the many lakes and tarns which form the principal feature of the scenery on any large and broad accumulation of moraine.

The second example of the local production of blue ice in the body of a glacier is that afforded by the lakes and tarns referred to in the last sentence of the previous paragraph. Wherever moraine material is present in large quantity—and, in spite of its general scarcity, several striking cases can be cited from every district examined—these small and large lakes are a marked feature of the landscape. They are due primarily to the local effect of radiation upon the rock-strewn ice, or to the water borne by glacier streams. Differences in the disposition, differences in the thickness, differences in the composition of the rock mantle, all produce local irregularities which usually tend to cause the surface of the ice to become an irregular mosaic of ridges, peaks and hollows. In the trough of every undulation, and in every little local hollow, the thaw-water collects to form lakes whose size is dependent upon the shape of the depression, and whose volume upon the relation between the amount of water locally available and the efficiency of any means of drainage present. Drainage may be complete, in which case a layer of silt—or, if the lake has been fairly long-lived—algæ, will be the only relic of its former presence. If it is not complete, on the other hand, a body of blue ice will result which, as the ice moves further from the source of supply of rock, will be less and less accompanied by boulders, until finally the cause of its origin may only be inferred from the accompanying cryoconite holes which show where the rocks and silt have sunk from sight. Photographs of such lakes accompanied by a greater or less accumulation of rock are shown in Plates CXCIX and CC.

Finally, bodies of blue ice of quite different shape will be formed by the water-impregnated ice beneath the many thaw-channels which, in the height of a warm summer, seam glaciers such as the Ferrar. The latter is the one glacier on which the extreme thaw has been seen typically developed, but most Antarctic glaciers in coastal regions where much rock is exposed will have, in a normal season, one or two streams of fair size. These only run for a few weeks or days in a year, but they have an important effect on the ice beneath them. They will also frequently be partially filled with ice at the close of the summer season. Should accumulation permanently exceed ablation for some considerable time, the result might easily be the preservation of the watercourse with its contained "thaw-ice" as a relic of former more genial times. Such a lateral fossil thaw-stream, appearing later in section in a glacier cliff, might easily give the impression of a very persistent and thick stratum of air-free ice.

It is possible that some of the most prominent blue-bands reported may have had their origin in this way. Incidentally, it should be remembered that such thaw-streams will fill any crevasses in their path, and, in this way, many of the vertical ice-dykes already referred to must have been formed. Not only supraglacial streams, but englacial streams also, have been observed in Antarctic glaciers, and one of the latter in the Campbell-Priestley Confluent-Ice could be heard rushing through the ice some hundreds of yards back from the ice-face, and seen pouring out on to the sea ice, flooding the undulations into which the latter had been thrown by pressure, and forming miniature blue-bands of a temporary nature even upon this very unpromising foundation.

(iv) White-Banding.

It cannot be too clearly impressed upon the glaciologist not personally acquainted with Antarctic land-ice formations that the normal ice of the Antarctic glacier—with the possible exception of quite abnormal glaciers deeply trenched in rock valleys and almost stagnant—is not the blue ice usually encountered in more temperate regions. The face of any normal Antarctic glacier will appear white in reflected light (Plate CLXXVII), and the stratified appearance which is a most marked feature is not usually due to a distinct alternation of white air-filled ice with blue air-free ice. The blue bands just described are somewhat exceptional, in that they do not form any great bulk of the normal ice-face. They could all be removed without an appreciable diminution in the height of the majority of glaciers. The normal stratification always referred to when the layering of Antarctic glaciers is discussed, is that which is rendered visible by the ordered sequence of layers with varying air-content and varied texture.

That such alternations must occur in any normal glacier, formed under conditions where there is no appreciable melting even of the upper layers, has already been indicated when discussing the cause of formation of the thin blue-bands dealt with already. The formation of a crust through the agency of ablation involves inevitably a measure of change in the granulation of the snow beneath the crust. The smaller fragments of snow tend to disappear and the larger ones to increase in size and thickness at their expense. Even the formation of a crust due to the compacting influence of strong wind has the same effect, for the very inception of a crust by any means causes a plane of temperature discontinuity favouring further deposition of ice vapour. It is a fact in the Antarctic—as elsewhere, even when the temperature keeps below freezing-point—that, whether there is wind or not, a crust will gradually form on freshly-fallen snow. If wind is active, or if a fairly hot sun is operative, the crust tends to form at the surface itself. Conditions do occur, however, when the equilibrium is such that a crust also forms some few inches beneath the surface of the snow.

The formation of a crust being a matter of observation, and the tendency of a crust when once formed to grow at the expense of the crystals beneath it being a matter of safe deduction, the question which now arises is:—What are the factors that tend to differentiate the different layers isolated in this manner? All that is required to account

for the differences in composition in stratified ice, is an original differentiation carried some little way before deposition covers the layers, and thus removes them farther from the surface zone to a position where the weather, and especially the sun, has no pronounced influence. Once the differentiation has been initiated, it may, we think, be admitted that subsequent changes will proceed at a different rate in different layers, provided always that conditions remain such that water does not form and act as a dissolving agent, upsetting the sequence of changes that goes steadily on in ice at a temperature below freezing-point.

What factors are there which would tend to initiate such a differentiation? The answer is clear. At least one important factor is the seasonal snowfall; another, equally important, is the proportion of fine weather in the summer, when the sun is exerting its maximum effect in the transformation of snow to névé and névé to ice. The air-content, in particular, will vary according to the degree the snow is compacted by temperature and wind, according to the period that elapses before the next considerable snowstorm, and, finally, according to the intensity of the sun's action during the fine period. The resultant impermeability of the crust will be due to the combined action of wind and sun in these conditions.

The rate of growth of the grains will vary, other things being equal, with the season of the year, for the snow that falls in autumn and early winter will not be exposed directly to the action of the hotter summer sun, and will remain comparatively fine-grained until it has been covered and protected by subsequent falls or drifts from the direct action of the sun. This difference between the size of the grain of summer and winter "drift" (as distinct from falling snow) is a feature that will have been noticed by all Antarctic travellers. In the summer, drift will often be but knee-high with a breeze which, in the winter, would have raised the snow about one's ears.

In the variation of these two factors, there is cause for a sufficiently large differentiation to ensure that the resultant layers (packed closely together though they will be by the subsequent accumulation of snow above them, and large-grained though they may become during the centuries occupied in passing from the surface where the snow fell or drifted to the point, many miles away, where the layers finally outcrop at the edge of the ice-formation) will still be sufficiently different in texture and appearance to be quite plainly distinguished by the naked eye, especially at a moderate distance.

Examples of névé, of bubbly ice, and of ice from a blue-band are shown in Plates CV, XCVII and XCVI. The former is typical of the transition stage between snow and ice when—to use our own definition—the air spaces still appear in the boundaries between the grains of ice; the second is a sample of glacier ice which still contains enough air to appear white in bulk, but in which the grains have grown to such a size that the bubbles of air are mostly completely enclosed in individual grains.

The former is typical of the upper portions of Shelf-Ice (and probably of moderate depths of the Barrier), of Ice-Tongues and Piedmont-Ice, which receive considerable accumulations of snow *in situ*, and of any places on the face of a glacier where local accumulation of snow has continued for several seasons. It is also found in the first

layer beneath the snow of Highland-Ice gathering grounds. It is the first step in the consolidation of the snow to granular ice.

Bubbly ice may contain a greater or less content of air and be composed of granules of greater or less average size. It is mainly by such variation in air-content that it is possible to distinguish the gradations of the white-banding, the explanation of which is the principal object of the present section of the chapter. Often, on close examination of a cliff which from a distance has appeared quite plainly stratified, it has been difficult or impossible to make out differences in the ice sufficient to enable a description of the different bands to be attempted. A close examination and etching of the ice showed that the only real difference between the layers was a slightly greater air-content and possibly smaller grain of the white bands than of the bluish-white bands.

Such a slight difference could be explained quite simply, on the assumption that the white bands represented the accumulation of snow in the late autumn and early winter, the bluish-white bands that in the spring and summer. On the other hand, similar differences might well be expected between the ice of radically different years, such as, for instance, that of 1911–12 and 1912–13, respectively. Similarly, quite as great differences might have resulted from the different conditions immediately succeeding two different snowstorms in a sheltered position in the same summer. The difficulty is not to account for such differentiation as has taken place, but to distinguish between the similar results of several differing sets of circumstances, all of which seem perfectly normal, judged by the experience of the British Antarctic Expeditions from 1901 to 1913.

Before leaving the subject, one further fact should be mentioned—that, while névé is usually confined to the topmost layers of glaciers or ice-sheets, cases have occurred within our experience where bands of typical névé, as figured in the foregoing illustration and as defined above, have been observed alternating with bands both of whitish and bluish-white ice of far more mature appearance.

This is perhaps the extreme case of stratification, which has its parallel at the other end of the scale in the blue-bands already described and explained. It implies a greater variation of seasonal conditions, but not one greater than could be accounted for in the present climatic conditions.

The general tendency is for the air-content of the glacier ice to accumulate in larger and fewer bubbles as time goes on. This is correlated with a very slow increase in size of grain. Still, even under such circumstances, the white-banding of the Antarctic glacier persists to some degree even in ice which must be of considerable age.

The washing of a glacier face by sea water or by thaw-water will often obscure the white banding or may even remove it completely, but this is on a par with that thaw action which results in the formation of large bodies of blue air-free ice in the manner already described.

White-banding is worthy of particular emphasis, since this minute stratification—often with several bands in a single foot, more generally with several in a yard—is one of the chief differences in appearance between the ice of the Antarctic and of temperate

regions. Its persistence is undoubtedly due primarily to the low temperatures which prevail throughout the life-history of a glacier in this most frigid of polar regions. Another cause which doubtless favours its persistence is the comparative infrequency of vertical differential movement. It is to be noted that the cases, which frequently do occur, of Antarctic glaciers which do not show marked stratification at their lower end, are invariably those where either (1) descent over rough ice-falls has caused a marked brecciation and the inclusion of much extraneous snow in the crevasses, or (2) stagnant glaciers deeply entrenched in rock valleys.

Of the former type of exception, any glacier with markedly steep portions may be taken as an example, such as portions of Warning Glacier, where the original stratification is completely obscured in the lower layers. As an example of the latter type may be cited portions of the Ferrar Glacier, where blue-bands play a much more important part than in most other glaciers.

(v) Pressure Ridges.

The phenomena so far treated in this chapter have been those which are best visible on the perpendicular face which forms the characteristic termination of the majority of Antarctic glaciers. We now have to consider certain occurrences, common alike to Antarctic glaciers and to those of other regions, and which do not greatly differ in different climatic zones. These are mainly the result of strains and stresses set up within the ice, which has essentially the characteristics of a rigid body, in that it is unable to adjust itself quickly to sudden stresses without fracture. According as the forces applied are those of pressure or tension, we have the formation of pressure ridges or crevasses. Differential forces applied to different portions of an ice mass will produce such fractures as shear-cracks, faults and overthrusts. The latter are often exceedingly well shown up by the presence of well-marked silt-bands along a glacier face, and good examples are shown in Plates CLXII and CLXIII, which show yet another portion of the face of Warning Glacier.

Plates CLXIV and CLXV show the adjustment of a glacier to forces more gradually applied with resultant overfolding, which is clearly shown up also by the convolutions of the silt-bands.

The result of the application of steady pressures is dealt with in the chapter on the mechanism of glacier motion, and it is only when pressure is applied at a rate too great for such molecular adjustment to take place that actual overthrust and fracture are caused.

If we consider first the origin of excessive pressure within an ice-mass, we find that such pressure may be due to one or more of several causes amongst which the most important are :—(*a*) Constriction of the glacier within narrower limits than higher up its valley ; (*b*) Obstructions in its course such as prominent promontories or rock islands ; (*c*) The meeting of two glaciers, or the pouring out of a moving glacier on to a coast already occupied by a mass of Piedmont-Ice, Confluent-Ice or Shelf-Ice ; or (*d*) The influx of another body of ice as a tributary glacier. In all cases, the results

of pressure are similar, but each type is of sufficient importance to justify some consideration on its own merits.

(*a*) It often happens, in the valley of a long glacier—in fact, it may be said that it usually happens—that the width of the valley is by no means constant throughout its length. Whether the valley be one inherited from a preglacial topography, or one gouged out by the ice itself along a natural line of weakness such as a great tectonic fault or trough, differences in hardness of the rock over which the glacier passes and through which it scoops its way will result in the quicker denudation of some stretches than of others. The result of these constrictions is seen in a piling up of the ice as it passes through them, though the piling up doubtless results in an increased scouring action, which causes the deepening of the valley, and in this way helps to accommodate the extra thickness of ice without causing its surface to slope uphill to an excessive amount. The effect of such a constriction on the surface of the ice is seen in a series of pressure waves disposed more or less symmetrically about the shoulders of the constricting portion of the valley (Plate CLXVI). Pressure waves are formed against the obstructing rock, sometimes with cracks at the crests of the undulations. Should the movement of the glacier be very quick, a heterogeneous confusion of ice-blocks may result from the bursting of the ridges and the shearing of blocks over each other through the endeavour of the ice mass to adjust itself rapidly to the new conditions. A marked feature of the troughs of the undulations produced in such pressure is the most disconcerting of all types of crevasse—that which is quite narrow above but widens out below.

(*b*) Pressure ridges on a similar scale may be caused anywhere in a glacier where, as so often happens, some great obstruction, such as a rock-bar or nunatak, interposes itself across the path of an active glacier. In such a case, the ice will be heaped up high in pressure waves before the nunatak and, if restricted passage exists on either side, the pressure waves will tail off into a series of ice-falls where the ice pours with accelerated velocity over the (generally) steep slopes on either side. Excellent examples of such concentric pressure waves and lateral ice-falls are to be seen on many Antarctic glaciers. Amongst the best known may be cited that of the ice pouring round the Reeves Nunatak in the glacier to the south of Mount Nansen. A smaller but more asymmetrical example is presented by the pressure at the back of the so-called "Solitary" Rocks of the Ferrar and Taylor Glaciers. Here, the ice only has passage at the present day over the south side of the bar, the northern flow being now entirely cut off. A third example is that of Heald Island in the Koettlitz Glacier. The most classical Antarctic instance of pressure round a prominent peninsula is that at Minna Bluff on the Ross Barrier. Here great pressure waves are found miles away from the point, while the presence of a continuation of the Bluff as a sub-glacial obstacle is perhaps suggested by the occurrence of a great system of wide crevasses to the northward of the Bluff.*

* The whole question of pressure on the Barrier is dealt with in the general description of that formation in Chapter VI.

(c) and (d) The remaining cases where pressure may be set up in an ice-sheet are so closely allied that they may be adequately treated under one heading. Amongst them occur the most important of all cases of pressure. It is to cases such as these that the majority of dangerous pressure areas are due, while the greatest examples of pressure in glacier ice can often be referred to these causes. The primary cause is, of course, the impact of one body of ice into another, and the resultant ice-forms are very complicated. We have to consider the movement of the glacier and that of its tributary, or, alternatively, the movement of more than one glacier impinging in different directions upon a more stagnant ice-sheet. When movements are in different directions the result is a cross-pressure which is distinctly reminiscent of a cross-sea raised by two conflicting winds; where movement is that of a swiftly-moving ice mass into a more stagnant body, as of a great glacier like the Beardmore or Denman Glacier into the Shelf-Ice along the coast, the resultant pressure is on a most magnificent scale, and will often be accompanied by the shear-cracks which will be considered later.

Perhaps the most specialised product of the cross-pressure produced by the impact of two bodies of ice moving in different directions (not necessarily at widely different angles) is what Amundsen has described under the name "hay-cocks." These he met during the early part of his journey across the Ross Barrier south of Framheim. They consisted of blocks of ice reared on end very much in the shape of a haycock, and were associated with a central hole and radiating crevasses. Similar phenomena were observed by the present writers on several glaciers, especially at the junction of the Murray and Dugdale Glaciers in Robertson Bay. They occurred at the intersection of two pressure ridges which were cracked along their crests, and the most apposite analogy to them is the case of the pyramidal waves of a cross-sea.

They should not, however, be confused with a somewhat similar appearance often met at the junction of crevasses of two different systems disposed at angles. These latter often survive after the original crevasses have been recemented, and remain in the form of a deep steeply-dipping, sometimes vertical, hole. The resemblance to the "hay-cock" pressure structure is simulated at a later stage by the formation of a deposit of hoar frost from the "breathing" of the crevasse.

The extreme case of pressure could not be better illustrated than it has been in the description by the British Australasian Expedition of 1911 to 1914 of the tearing action exercised by the great glacier which forces its way through the ice of the Shackleton Shelf-Ice in Queen Mary's Land.* Here, blocks of ice have been thrust over one another, and torn off and tortured into a chaos which is quite impassable for sledge parties. Similar pressure phenomena on a slightly less extraordinary scale are observed where the Beardmore Glacier forces its way into the Ross Barrier. From a point on the slopes or summit of Mount Hope, the glacier can be seen ploughing its way through the more

* D. Mawson, 'The Home of the Blizzard.'

stagnant Shelf-Ice on either side for miles. As the ice stream is gradually brought to rest and its energy dissipated upon the Barrier, the zone of chaotic pressure dies away in long, more or less concentric, ridges and troughs which gradually flatten out until, far in the distance, the Barrier once more appears level to the eye of the observer. Actually, observations show that the pressure has effect much farther than the eye can see. Similarly, as the Ross Barrier itself—moving as the result, partly of the accumulation of snow upon its surface, partly of the thrust of the great glaciers which feed it—surges past Ross Island and King Edward's Land to its dissolution in the Ross Sea, once again huge pressure waves are piled up against these obstacles.

(vi) Crevasses.

As pressure waves are the invariable result of pressure, so crevasses are the inevitable result of too great tension where glacier ice is passing over an uneven bottom or round a curved portion of a glacier wall. The crevasse is a feature which has always been the anxious study of the Antarctic explorer, for, with the possible exception of the vagaries of sea ice, there is nothing so liable to bring his plans to naught and, at the same time, to cause loss of life or injury to limb. That more loss of life has not been caused through the agency of the Antarctic crevasse is due partly to the fact that they have been taken very seriously and partly to the operation of a factor we may recognise as we please under the title of Providence, Good Fortune, Fate, or Luck. Certainly, this fortunate fact has not been due to absence of crevasses, for, given the same amount of ice passing over the same irregularities at the same speed, there will be more crevasses on an Antarctic glacier than on a glacier in warmer climate. Low temperatures reduce the power of molecular adjustment of ice to tension.

The causes of the formation of crevasses in the Antarctic glacier do not differ except in the degree of their operation from those in other regions. They have been dealt with in sufficient detail in the chapter on the "Mechanism of Glacier Motion." One subsidiary cause of fracture which is more of academic than of practical interest is, however, sudden change of temperature. Changes of temperature of considerable amount take place with startling suddenness in the Antarctic climate, and the effect of these upon sea ice is of decided importance and is noted elsewhere. The principal example of a similar effect on glacier ice is the fusillade of reports which follows the dipping of the sun behind a rock bluff as evening draws on. The sun, which is fairly high in the sky, and is therefore exercising considerable power, is suddenly withdrawn from operation; the chill breeze from the plateau continues to trickle down the neighbouring valleys and, within a few seconds, a bombardment of reports and sounds like the shivering of glass announces the fracture of the surface ice in the attempt to adjust itself to the new temperature conditions.

The distribution of Antarctic crevasses is exactly what might be expected from the cause of their formation, and does not differ at all from that in glaciers and icefields in other parts of the world. If ice descends steeply over uneven ground, ice-falls will

result (Plates CLXVII and CLXVIII). If ice passes over a submerged bar, as at the entrance to the Priestley Glacier, a remarkably regular series of cuts will mark the exact degree of its adjustability and speed (Plate CLXIX). If ice passes round points projecting from the walls of its valleys, radiating crevasses will result. The usual crevasses will be found caused by differential movements within the body of a glacier. The only difference found in the Antarctic glacier is, as already emphasised, that crevasses will appear on the slightest pretext, such as passage over the most slightly undulating ground (Plates CLXX and CLXXI). The occurrence and distribution of crevasses is perfectly normal. It is their life-history, and particularly the modification they undergo, which is most interesting both from the explorer's and the glaciologist's point of view.

A crevasse differs in appearance according as it has resulted from a shear or a tension. This is well shown by an examination of the interior of any crevasse which has undoubtedly owed its formation to one or the other agency. If the crevasse has been formed owing to passage of the ice over an uneven bottom, it tends to have straight uniform sides for considerable distances, the chief irregularities in the sides being due to great ice pinnacles only partly torn away and sticking up from the bottom of the crevasse like huge teeth, or, rather, like the stakes set in the native dead-falls used to trap big game in Central Africa. A similar pinnacle left standing at the face of a cliff after the calving of a berg is shown in Plate CLXXII. If the slope over which the ice moves is very steep, this statement requires considerable modification, for, in this case, the cracks are usually longitudinal as well as transverse, resulting in the formation of seracs. The effect of a straight-splitting fracture is, however, well seen in the cliff face of the end or side wall of almost any Antarctic glacier, the most striking feature of which is undoubtedly its smoothness and freedom from irregularity. The tendency to plane or flattened conchoidal fracture is marked in Antarctic ice and is reflected in the contours of crevasses and cliffs.

If, however, the crevasse owes its origin, as it so frequently does, to a fracture such as that produced by the onthrust of another glacier, the effect of the shearing or tearing component is frequently well seen in the structure of the crevasse itself, which is often discontinuous with bridges of unbroken ice swung across between the interrupted elements of the crevasse. A similar structure is produced on a more marked scale in sea ice under the same conditions, and is figured in Plate CCXL in the chapter on Fast-Ice.

The effect of the recemented crevasse in the formation of vertical blue-bands across the face of a glacier has already been referred to in a previous section, but mention may here be made of the possibility of the transverse crevasse having a distinct effect as an element in the horizontal stratification. The fact that the upper and centre layers of ice in a glacier move quicker than those at the sides and bottom, will result in the gradual turning of such a crevasse through almost any angle less than 90 degrees. A vertical transverse crevasse may thus end as an almost horizontal one with upturned edges. Such a crevasse, if filled with blue ice, would appear in the cliff face as a well-

defined long thin blue-band, and the possibility that some blue-bands on the faces of Antarctic glaciers may have been formed in this way should not be ignored. This fact is illustrated in Fig. 90, where five points from top to bottom of such a crevasse have been taken along a vertical section in the medial region of the glacier. Fictitious values of movement of the ice at these different heights have been taken, and the position of the points plotted at the place of formation of the crevasse and at 1, 2, 3, 4 and 5 miles down the glacier. If, then, the cliff face of the glacier appears at any point just short of the fifth mile, it will be seen that the blue-band at a height between points E4 and E5 will outcrop on the face as a more or less steeply dipping horizontal stratum. If such a crevasse were filled with silt, the band would crop out as a horizontal silt-band, but reflection on the conditions actually obtaining in an Antarctic glacier tends to the conclusion that regular silt-bands are not likely to occur as a result of such a process.

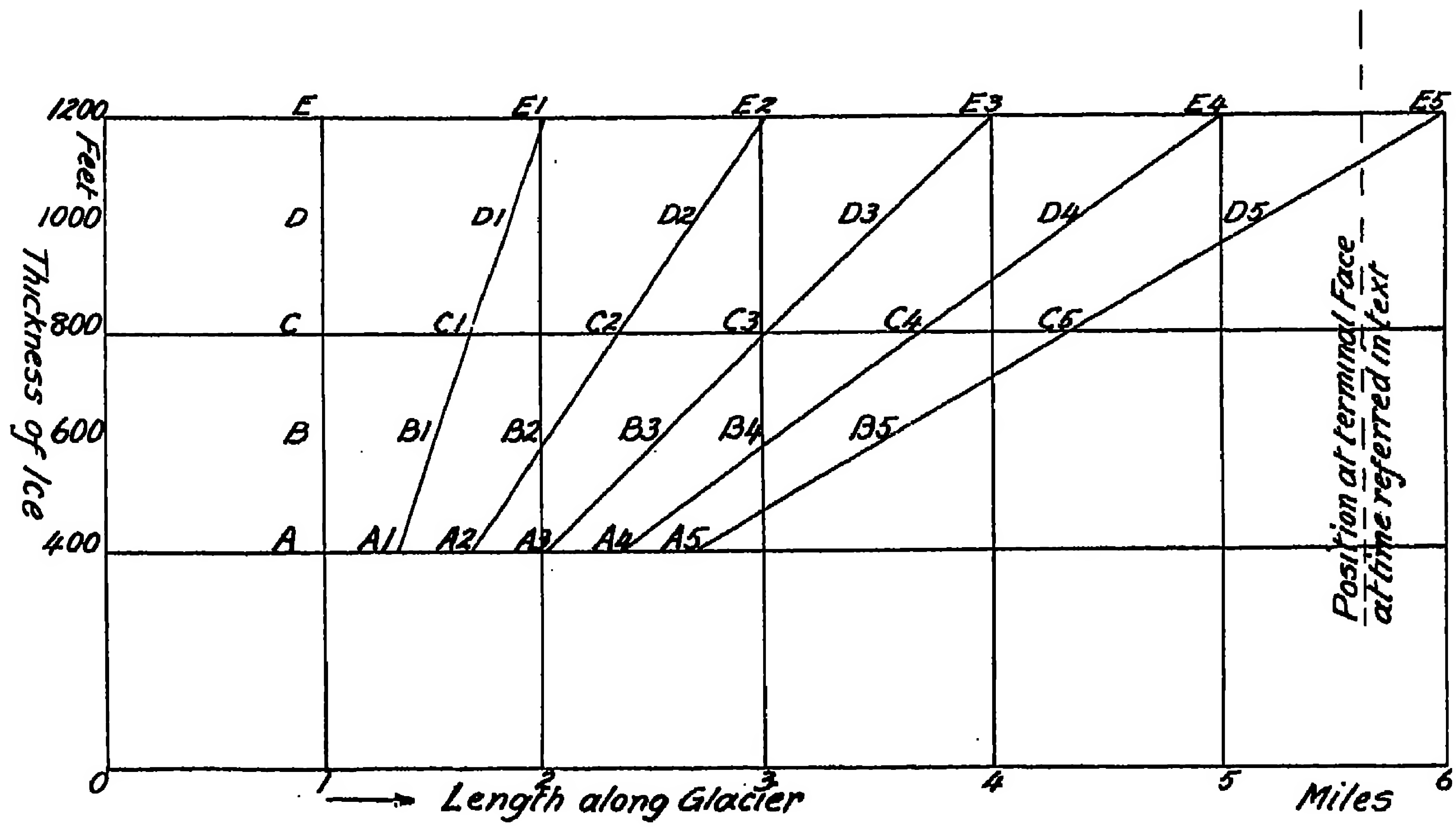


Fig. 90.

The length of life of crevasses will depend in great measure on the speed of movement of the ice of the glacier in which they are formed. As the ice reaches a less uneven portion of the bed, the crevasses of the normal ice-fall will close up, and be recemented more or less perfectly according to the amount of snow and other extraneous matter that has found its way into them during the period through which they have remained open. The obliteration of a crevasse will be more or less complete according to the same factors, and the evidences of the former occurrence of the wide gap may either be entirely wanting, may be a plane of no appreciable width but outlined by a greater air-content, or may be an ice-dyke of pure ice or of a mixture of snow and ice. A notable example of such planes of former discontinuity, outlined only by a difference of air-content, was observed just below the ice-falls to the north of the Solitary Rocks on the

Ferrar Glacier. For some two or three miles below the falls, the ice was seamed with two or three sets of such planes which agreed in general direction with the crevasses at the ice-falls. As the ice-falls were approached, the cracks commenced to open further and further, demonstrating without doubt that the series of lines seen further down the glacier were the survivals of the gaping crevasses of the falls.

It is an interesting fact that ice traversed by such planes does not necessarily tend to break along the plane itself. The latter appears often to be a plane of strength rather than one of weakness, and the normal conchoidal fracture of the ice will take place at any angle to it, as also along it. In some cases the plane may be outlined by the inclusion of dust particles also; but this is uncommon, since the occurrence of any quantity of wind-blown dust presupposes usually a sufficient amount of snow in the crevasse to cause more than the formation of a simple plane of air-bubbles.

When grit occurs, the crevasse is usually only imperfectly closed, masses of grit and snow being enclosed along its length as irregular blobs of brownish and whitish ice.

An incidental effect of the formation of crevasses in an area characterised by strong wind and heavy snowfall is the formation of snow-lids to the crevasses. These have been carefully studied by different expeditions, since the safety of a party frequently depends upon the strength or otherwise of snow-bridges. Within the experience of the writers, crevasses up to 130 paces wide have been observed which have been completely bridged. Some diversity of opinion exists as to the exact section of the bridges, and it is truly not easily determined; but, in some cases which have been carefully examined in the present Expedition, the cross-section of crevasse snow-bridges was as shown in Fig. 91.* Such a crevasse lid has two marked areas of weakness as a bridge for a sledge party, one at each side of the crevasse. The dangerous area is, however, that at the side nearest to the direction from which the prevailing *strong* winds blow. Here the snow-lid tapers out to a fine point, and it is at this point that the lid is most likely to give way. It is a point of general interest that, as a rule, crevasses over 15 to 20 feet broad are usually bridged quite safely for the transit of any sledge party not striking them very obliquely. Those most likely

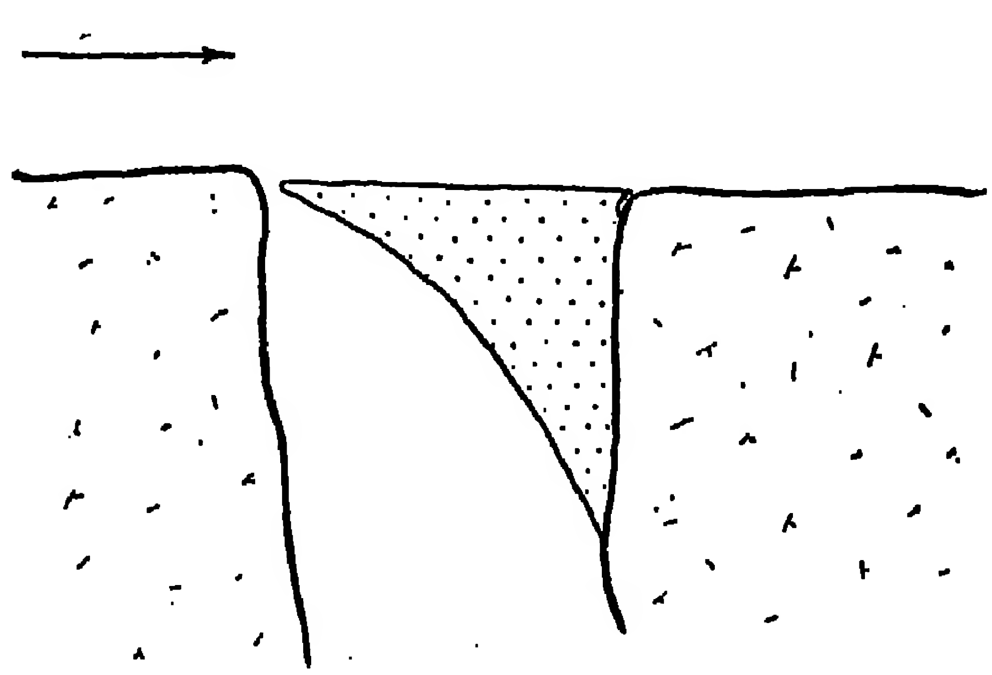


Fig. 91.

to cause some trouble are crevasses between 4 and 20 feet broad. The lids formed over such crevasses are likely to be strong enough to bear the weight of the number of men who will be on them at the same time if they are being crossed at right angles. If, however, their direction is not obvious, it only requires a slightly

* Crevasse lids have also been seen which owed their formation to the outgrowth of a cornice from the *windward* wall of the crevasse.

oblique angle to render them distinctly unsafe. Plate CLXXIII is a photograph of a section through crevasses that are almost entirely snow-filled, the filling taking place probably by the subsidence of a series of snow-bridges.

When first formed, the edges of a crevasse are sharp and their walls are clean and usually sheer. This state of things does not last, however. The tendency is for the air in a crevasse to be kept at a different temperature and to have a different vapour-content from that above. There is constant circulation due to the convection which may be set up in this way, if the temperature conditions are favourable. Both in winter, when the air of a crevasse is often, or usually, of higher temperature than that above it, and in summer when constant changes of temperature and sunlight cause an exaggeration of the action, the formation of snow crystals on the walls and on the under side and within the lids of crevasses is continuous. Multitudes of these crystals are shaken down into the crevasse to form part of the accumulation of snow and ice always tending to fill it up, but, as all explorers who have fallen down a crevasse will readily admit, masses remain to festoon the upper portion of the sides and the lid. The types of crystal produced, their habit of growth and their structure are dealt with in another chapter.* They are mentioned here as being a feature in the life-history of the normal glacier, and as having a distinct bearing upon the way crevasses are filled up and obliterated even in stagnant ice-falls.

The normal ice-fall in a slowly moving ice-sheet does not show clear-cut gashes going down towards the bottom of the glacier. The usual appearance of such a fall is a mass of rather rounded tumbled seracs, with their original clear-cut faces profoundly modified by ablation, drift-chiselling and thaw, and with their lower portions filled with a heterogeneous mixture of ice-blocks, pieces of snow fallen from the lids, masses of crystals shaken from the walls, and, often, in favourable situations, of wind-borne gravel and dust and of fragments weathered from the rock walls on either side.

Similarly, the greater and more regular gashes in a glacier caused by passage over a rock-bar or by the surging of the ice past a rock promontory or island, if not quickly closed as they are in a glacier moving at a fair speed, are soon modified by the same processes. Typical examples of altered crevasses on the Priestley Glacier are shown in Plates CXXVII and CLXXIV. Here the thaw is relatively intense, and many of the crevasses have become the beds of thaw-streams so that their bottoms are often covered with water-strewn gravel. The edges of their walls are rounded by ablation and by thaw, and are grooved where little trickles of water have run over them to join the larger rivulets below. Very few holes continue for a greater depth than 10 or 20 feet, and many *ci-devant* crevasses have now been widened until they have assumed a typical, though somewhat elongated, tarn-basin form.

Finally, some mention should be made of the brecciating effect of great ice-falls on the glacier structure immediately below them. A section of such a glacier will

* Chapter II.

show a most confused ice structure, which is evidenced by the persistence of the visible stratification in the individual blocks. Such a structure may continue to be recognisable for a mile or more down the glacier,* and this is but another example of that most characteristic feature of the cold climate glacier—the persistence of original structures, owing to the absence of thaw-water to bring about drastic modifications.

(vii) Shear-Cracks.

Before finally leaving the subject of structures caused by the stresses due to glacier movement, one particular type of crevasse seems to merit consideration by itself. One result of differential movement, whether within a glacier or between two glaciers, is the shearing apart of the masses of ice moving at sufficiently different speeds and the formation of shear-cracks which, in the latter case, are often so broad as to assume the appearance of inlets of the sea. In the case of shear within a glacier, the tendency is for the crack to remain small, since the pressure of the ice pent up between rock walls is too great to permit any swinging apart.

Such little shear-cracks up and down a glacier have several times been observed, while their former presence is often indicated by the occurrence of planes marked by air-bubbles which are not likely to have been produced in any other way. On the Priestley-Campbell Confluent-Ice, just beyond the point of outflow of the Priestley Glacier, such shear-planes were much in evidence, but unfortunately they do not show up well in the photographs which were taken to illustrate them.

When the shear has taken place through the driving action of a great ice mass moving with considerable speed through a more stagnant sheet, or through the differential movement of two great ice-sheets moving outwards over the Continental Shelf in water deep enough to float their seaward terminations, the most striking cases of these shear-cracks occur. Such, for example, are Relief Inlet and the great crevasse encountered further to the north of the Drygalski Ice-Tongue by the Northern Party of the present Expedition. (Map XIV.)

Such, also, in all probability, are the great crevasses reported by Amundsen as running back into the Ross Barrier at Framheim. (Map II.)

In the first case, we have the Drygalski Ice-Tongue shearing its way past the more stagnant ice of the Campbell-Priestley Confluent-Ice, which, whatever may have been the case in the past, certainly no longer taps the Continental-Ice to any extent. The end of the tongue, moving freely on the surface of the Ross Sea, permits the growth of the shear-cracks to a considerable width.

Relief Inlet itself was some half a mile wide near its mouth in 1913, when it was crossed by the Northern Party within a short distance of its seaward end. No snow-bridge could be expected to span the broad space between its low cliffs, but its place was efficiently taken by thick sea ice. The lesser shear-crack to the north, though 130 yards broad at the place where the party crossed it, was intermittently covered with thick snow-bridges, but its course could be traced as far as the eye could reach,

* As in the Suess Glacier entering the Taylor Dry Valley.

partly by the different shades on the snow-bridges and partly by the intervening openings It was at least 4 or 5 miles long, and, in all probability, continued much farther back than we could see.

It is unfortunate that no very clear idea of the Framheim shear-cracks can be gleaned from Amundsen's popular account of his Expedition.* It is, however, fairly clear that the probable cause of these marked planes of weakness in the Ross Barrier ice, is the junction line between the Barrier and the more slowly moving ice of King Edward VII Land.

Indeed, it seems in the highest degree probable that the persistence of the Bay of Whales for several seasons in the same identical shape, may be due to the occurrence of this junction line, with its attendant planes of weakness, between land-borne and sea-borne ice of different derivation. The Barrier at this place appears to have broken back according to a definite plan, and it is likely that the occurrence and the direction of the shear-cracks have been deciding factors.

(viii) Form of Glacier Snout and Wall.

The radiation gully which is characteristic of Antarctic glaciers is dealt with in the chapter on "Ablation and Thaw."† Its physiographical significance will no doubt be discussed fully in the Physiographical Memoirs of the Expedition. Some discussion is necessary, however, of the typical contour of both sides and termination of the majority of Antarctic glaciers—the vertical cliffs which are their most picturesque feature, and which appear to be largely confined to the glaciers of polar regions, and to be developed to their greatest extent in the great ice-formations which are confined to the Antarctic.

The characteristic vertical side-cliff of the Antarctic valley glacier is due to the predominant effect of radiant heat on the walls of the glacier over that of thaw-water on its surface. What little water there is, is not sufficient to outvie the thawing effect of the heat-waves from the steep rock cliffs, while the concentration of the streams in the radiation gully itself often tends to undercut the glacier cliff and keep it more nearly vertical than it otherwise would be.

The second factor which leads to the formation and preservation of the side-cliff of the normal glacier is the scarcity, or absence, of lateral moraine. Where moraine occurs in large quantity, the ice-cliff is much rounded, or may be absent altogether, as in the photograph of Corner Glacier shown in Plate CLXXVI. A striking instance of the effect of even a few rocks as a strictly lateral moraine is afforded by the face of the Glacier on the south side of the outer Solitary Rock on the Ferrar Glacier. Here the rocks are comparatively scarce, yet they have been able to lower the surface of the portion of the glacier on which they lie 6 feet or more. The height of the lateral face of the glacier is thus reduced by this amount, the moraine lying on a lower terrace and

* Roald Amundsen, 'The South Pole.'

† Chapter VIII.

bounded on the side nearest the main glacier by a steeply-curved little cliff some 6 feet high.

A similar obliteration of the radiation gully and cliff may be brought about by an accumulation of snow (in which case its former presence can sometimes be recognised by variations in the stratification of the ice exposed in the terminal cliff), or by the absence of well-defined rock walls, in which case radiation does not act so powerfully.

In the wall-sided glacier, the tendency is for the walls of the glacier to remain vertical if movement is taking place to any great extent, or even where movement is very slight. Examples of vertical and curved sides to wall-sided glaciers are given in Plates CXIV and CXV.

In the first example, the overhang of the glacier is steep and the verticality of the sides is kept by the frequent fall of avalanches usually separating along vertical planes. In the other case, the slope is more gradual and the example is taken from a situation where the power of the sun is more effective than is usual in South Victoria Land. Much of the verticality of the walls of small glaciers which are practically without movement is due to the greater content of silt in their lower layers. Radiation from the sun and sky tend to melt back these lower layers quicker than the upper, with the result that overhang takes place and is from time to time adjusted by avalanche. This undermining along siltbands is most marked during the Antarctic summer, and it should be placed on record that no cases have been observed in the Antarctic by the present writers, of overlap due to the quicker movement and consequent jutting forward of the upper layers of glaciers. This has been found by Chamberlin in Greenland glaciers, and its absence in this portion of the Antarctic may possibly be due to the fact that all rapidly-advancing glaciers examined by the British Expeditions have their termination in a free floating tongue in the sea.

The very nature of the Antarctic glacierisation prevents evidence being obtained from examination of the terminal cliffs of swiftly advancing glaciers, to support any theory of movement by overthrust within the mass of the glacier. As with the case of moraine material, conclusions against the truth of this conception cannot be deduced from the lack of evidence in its favour. The natural home of the end of a vigorous Antarctic glacier is the sea, where it advances freely over a frictionless plane in response to the stimulus of accumulation along its length and on its gathering ground. It is the sea also which determines the angle of the terminal face of such Antarctic glaciers as do not push their way into a greater ice-sheet.

Little hanging glaciers will have vertical or sloping faces according to circumstances, as they have vertical or curved side-walls. The vast majority of the greater glaciers of South Victoria Land end as steep cliffs which have their lower portion bathed by the sea in summer and ground by the edge of the sea ice in winter. From time to time, bergs separate, also with vertical sides, and the result of all this action—and in particular of the undermining work of the sea—is a uniform vertical cliff of ice sometimes hundreds of miles in length (Plate CLXXVIII). Where, exceptionally, a glacier ends

short of sea-level, its snout is sometimes rounded under the influence of thaw water coursing down its sides and dust or rock *débris* deposited on its surface, but these cases are so infrequent that they scarcely demand detailed notice.

Summary of Differences between Antarctic and other Glaciers.

A scrutiny of the material set forth in this chapter will make evident certain features in which Antarctic glaciers and ice-sheets differ from those of other regions which are of similar form and disposed upon rock-bases of similar contour.

In the Antarctic, moraine is less common; siltbands also are less frequent; stratification is more marked and the conservation of all original ice and snow structures is a feature which is perhaps more impressive than any other. All these typically Antarctic features may be correlated with a climatic difference which seems to be the deciding factor. The Antarctic winter is comparable with that of frigid continental regions about the North Pole; the Antarctic summer is unique and is the direct or ultimate cause of most of the phenomena mentioned above.

The absence of any great extent of surface moraine is undoubtedly caused by (1) the comparative scarcity of exposed rock, (ii) the small speed and therefore slight lateral erosive power of Antarctic glaciers, (iii) the tendency of scattered surface moraine to become englacial. The absence of visible ground moraine or terminal moraine can be directly correlated with the degree of glacierisation and shape of the continent, and is comparable only with the corresponding countries around the North Pole (*e.g.* Greenland), where a similar, if less intense degree of glacierisation is met with. The ultimate cause of both is the absence of a warm summer. The absence of thaw water, again, considerably reduces the speed of movement of glaciers as compared with sister ice-formations of similar size and slope in warmer climates. This must have a distinct effect in reducing the accumulation of moraine of all descriptions and there seems little doubt that, size for size and slope for slope, the present Antarctic glaciers are much more inefficient than equivalent formations in the north polar, or in more temperate latitudes.

Bound up with the small proportion of moraine on, and in, large Antarctic glaciers, is a similar small content of silt, and this, in its turn, much tends to reduce the effect of such summer heat as is experienced in high southern latitudes. Perhaps, however, this effect is more apparent than real, for one marked difference, also to be correlated with the absence of a well-defined "thaw" season in the Antarctic, is the survival, more or less in place, of much of the silt that lies on the surface of an Antarctic glacier. There is usually no great amount of running water to wash away the silt that has weathered out at the surface during the summer. The dust in turn sinks under the influence of the sun and is exposed by ablation during cold spells. If circumstances are particularly favourable, the same silt may lie on a glacier, or sufficiently near to the surface to exercise a thawing effect, throughout an entire season.* In any warmer climate, the dust would

* Observation shows that small patches of silt do not sink more than 12 inches into the ice. Their downward progress is stopped at this depth owing to the low altitude of the sun in these latitudes.

undoubtedly be swept off by surface thaw water and carried into the body of the glacier or down its valley by streams. Another effect of scarcity of running water in the Antarctic is seen in the persistence of fossil ice-slabs for long periods. There occur instances of stagnant masses of ice, such as that lying under the lateral moraine of the Koettlitz Glacier, which, owing to the veneer of rock material which covers them, show little sign of diminution from year to year. It is interesting to speculate, in such situations as Ross Island where many rock-clad slopes exist, how much of the rock is the surface mantle of weathered lava and how much is simply surface or englacial moraine resting on such ice-relics.

Apart from the question of rock and silt, stratification—and particularly stratification in the lower portion of a glacier where it is less likely to be the immediate product of the processes of the present day—must be most pronounced where the summer temperature is not high. This is perhaps the most striking of all the peculiar features of Antarctic land-ice. It appears to be even more characteristic of Antarctic than of Arctic ice-sheets, though, as might be expected, the glaciers of Greenland show stratification to a greater extent than those of more southerly latitudes in the northern hemisphere. This is the direct result of one of the most interesting points about the Antarctic climate, that is, the comparative rigour of the summer months even at sea-level. The summer temperature of the southern continent only exceptionally rises above the freezing-point of fresh water. That most active of all denuding agents as regards effect upon ice—running water—is practically unknown for more than a few weeks in the year, even in the most favourable circumstances. Many of the greatest Antarctic ice-sheets, such as the Ross Barrier, are not affected by running water at all, except at their borders, and, even here, its action is extremely local.

Within the body of the normal glacier, water plays a completely subordinate part, its only result being the formation of the larger of the local bluebands which have been described. The great majority of the changes which go on during the life history of the Antarctic land-ice formation are brought about by molecular movements. They are essentially molecular changes operating in the most frigid conditions and therefore at a minimum rate. The preservation of stratification, long after its inception and throughout a considerable modification of grain is pre-eminently an Antarctic characteristic. In some degree, this is of use as rendering possible more detailed elucidation of the way in which névé grows from snow and ice from névé. The initial changes—usually uncomplicated by the presence of water—may be seen in any snow-drift in the summer. The subsequent growth of the grains at later stages in the life-history of the ice can be demonstrated by etching, either by means of ablation or of exposure to the air at temperatures just above freezing-point. The absence of water is in many cases absolutely certain, so that the formation and growth of Antarctic ice must be considered entirely apart from this factor. In all other countries, water plays a more important and, indeed, usually a dominant part, resulting in the formation of ice of much larger grain and with less air-content than is usual in the Antarctic.

While the uniformly frigid climate is undoubtedly the principal cause of the conservation of original and also of superimposed structures (such as ice-dykes, planes of air-bubbles, etc.) in glacier ice, one other factor should not be forgotten. This is the small even gradient of the majority of the greater Antarctic ice-formations. The greatest of the Antarctic valley glaciers descends some 9000 feet it is true, but does so only in 120 miles. Such a gradient can only be steep in parts, and there is possibly less tendency to brecciation and the formation of seracs in the Beardmore and other Antarctic outflows from the Continental-Ice than in the normally steeper and shorter glaciers of other regions.* If this is the case with the great "outlet" glaciers, how much more is this so in the gigantic ice-formations such as the Shelf-Ice, Piedmont-Ice, Ice-Tongues, etc. In all these examples, while a certain proportion of the material of the ice-sheets comes from the true glaciers pouring into them, a great quantity of ice is formed from the precipitation on the ice-sheets themselves. In the case of Shelf-Ice and Piedmont-Ice it is the rule that they owe the major portion of their mass to local precipitation. In these cases and in that of the Continental-Ice and many Highland-Ice sheets, the gradient is often exceedingly small. The ice moves steadily outwards under the stimulus of its own weight. There is little crevassing: no brecciation. When the ice arrives in due time at the terminal cliff, the original stratification—due in the main to the layering of the seasonal snowfall and snow-drifts—is unchanged. The only alteration is in a gradual growth of the grains of the ice of all layers in size, and the concentration of the air content into bubbles usually enclosed within the individual grains, instead of scattered as a film between the grains as in the original snow. This is true for all of the many great ice-sheets where the horizontal portion, advancing over a featureless plain or over the surface of the sea, is also the main gathering ground. Where gradients are steep and the ice broken up during its passage from top to bottom of a glacier valley, the original stratification may be obscured or obliterated without the intervention of water.

Pressure and crevasses are due ultimately not to climate but to contour of valley or bed. Where ice passes over uneven ground, rupture is certain to take place. Where constriction or obstruction takes place, whatever the cause and whatever the climate, there will pressure be set up and, in ice, excessive differential pressure will result in fracture more or less chaotic. The only generalisation that can be made is that, given similar masses of ice passing over similar slopes at similar speed, crevassing will be more likely to occur in the Antarctic than in warmer climates. Similarly, and this follows from the arguments already used in reference to stratification, once crevassing has taken place, the signs of it will persist longer in the colder area. Water will obliterate traces of crevasses, as of all other structures, in ice.

The radiation gully is a typically Antarctic feature, though sometimes observed elsewhere. It, again, is a function of the degree of glacierisation and of the climate.

* It must, however, be remembered that Antarctic glaciers will be *more* crevassed than glaciers of equivalent slopes in other lands with warmer climate. It is the absence of steep slopes which tends to counterbalance this effect.

B 4

Less surface moraine, absence of large volumes of thaw water, and long periods of direct sunlight upon such rock slopes as exist, will be the ideal conditions for the formation and preservation of such a gully. When gales of extreme force are added as a constant feature of the weather, the formation of gullies round rock exposures bordered by accumulated snow-drift will be much more frequent. Wind action throughout the year, and the sun's heat in summer, ensure the existence of a considerable hollow between all types of ice-formation and their rock-walls, or rock islands, except in the most profound lee or where the movement of the ice is comparatively swift against or past the rock. At the place of infall of a tributary; at a constriction of a valley; where the ice-mass is shouldering round a nunatak, where moraine is more than normally prevalent, the radiation gully may be absent. Normally, it will be a feature of any rock-bound border of an ice-sheet where the rock-walls overtop the surface of the ice. This is shown in many photographs of Antarctic glaciers and other ice-sheets thus bordered; it is another of the minor differences between the Antarctic glaciers and those of the temperate zone.

CHAPTER VIII.

ABLATION AND THAW, WITH PARTICULAR REFERENCE TO ANTARCTIC GLACIERS.

In preceding chapters we have attempted to describe the modifications which the Antarctic snow undergoes after its deposition, omitting so far as possible those modifications which lead to its disappearance from the original surface, and to the erosion of that surface. At the same time, it must be remembered that changes undergone by the snow surface are often associated with the change of a greater or less amount of snow or ice into one of the two phases—liquid or vapour.

For instance, it will be noted that, under the heading "Modifications of Snow Surface due to Wind Action," it was stated that, though sastrugi of deposition were not uncommon, the most common forms were those caused by erosion. Thus in the case of a local blizzard, though the effect may merely be the shifting of a quantity of snow from one position to another, still the circumstance that the wind blows downhill roughly from the centre of the continent means that the ultimate effect of a number of blizzards will be to shift snow towards the sea, and finally to deposit a certain portion of it, either in the sea or on the sea ice. In either case, the sea itself is the ultimate repository of the erosion products.

In the example quoted above, deposition and erosion are working side by side—in the same place, at the same period of time, and through the same agency—and this dual action is typical of many of the processes which cause modification of Antarctic snow and ice surfaces. It will thus be seen that it is impossible to draw a hard and fast line between the processes of modification and of erosion of any particular surface.

In preceding chapters the changes—water vapour to snow, snow to névé, and névé to ice—have been treated in turn, together with the alternative change—water to ice—and from the evidence it should be clear that ice is the stable form of the compound H_2O on the Antarctic Continent. We can, in fact, visualise the operation as a complete cycle. The snow deposited on the plateau changes to névé and to ice; under the influence of gravity it flows slowly down to lower and warmer levels; here, the greater heat and the action of the sea causes the ice and névé to assume the liquid or the vapour phase. Meanwhile the supply of snow on the plateau is replenished by the deposition of water vapour. The velocity of change from phase to phase in this cycle must remain unchanged so long as climatic and geographical conditions do not alter. Until temperature conditions become more genial, and there is a consequent acceleration of this velocity of change, the preponderating amount of H_2O on the continent must exist, as at present, in the form of ice.

It is assumed that the first three great changes in the cycle "water vapour—snow—névé—ice—water or water vapour" have already taken place, and, in the present chapter, the modifications which the solid form (snow, névé or ice) undergoes in its change to liquid and vapour, together with the causes of these modifications, will alone be treated.

The agencies which give rise to these latter changes of phase, and the ice-forms which they produce, may be treated under two divisions :—(1) Ablation, and (2) Thaw. Under the heading "Ablation" will be considered all changes, however caused, which lead to the formation of water vapour directly from ice by sublimation processes. First, therefore, will be treated all those erosional effects of wind, temperature, radiation, exposure, etc., which lead to the removal of ice in the form of vapour. As a sub-division of this section, the mechanical effects of the snow and rock drift carried by the winds will also be discussed. The section dealing with "Thaw," on the other hand, will deal with changes leading to the formation of water from ice or snow.

Ablation.

Since ablation is here considered to include all changes leading to the formation of vapour directly from ice, it is obvious that the causes to which these variations in ablation are due will be those which modify the vapour pressure at the surface of the ice.

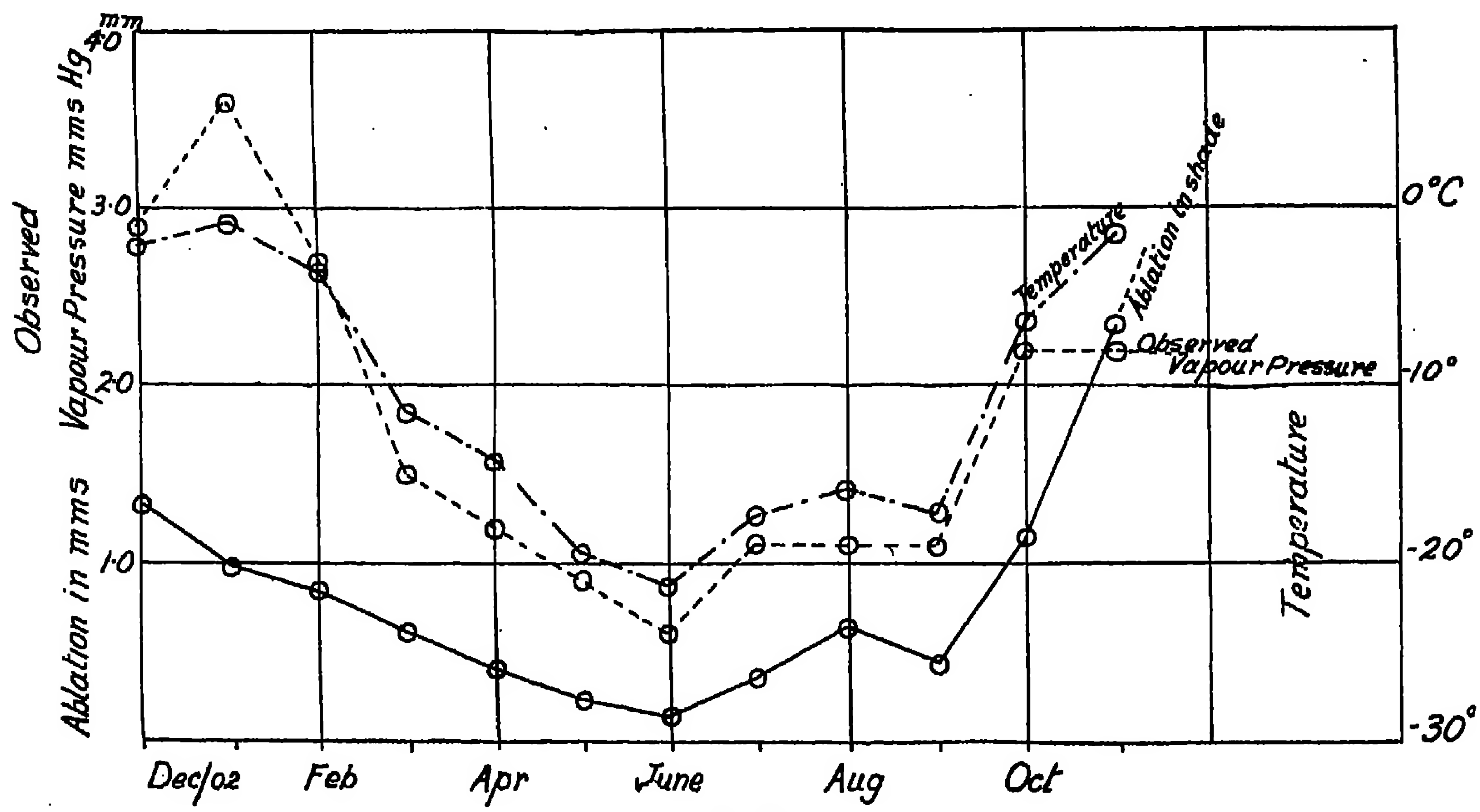


Fig. 92.

Vapour pressure depends on temperature (Table XXIV of Appendix). From this Table it will be noted that the vapour pressure at — 40° F. is only one-fiftieth that at 0° F. Moreover, the temperature coefficient of vapour pressure not being constant, but varying with the temperature, the absolute magnitude of the ablation will not be a linear function of this temperature, but will increase progressively as the temperature is raised. The temperatures we have to consider in this section will always be

below freezing-point, since temperatures above freezing-point will cause thaw, not ablation. We have unfortunately no absolute data on the amount of variation of ablation with temperature alone, but certain information can be obtained from an analysis of the results of experiments carried out by the Swedish Antarctic Expedition 1901–4, shown in Table VIII. This shows that the number of millimetres of ice evaporated in each month from an ice surface shaded from the sun is dependent on the mean monthly temperature, and roughly follows the changes in the observed vapour pressure. The figures in Table VIII are plotted in Fig. 92 the better to exhibit this relation.

These values of the ablation are independent of direct radiation from the sun and also, since, with the exception of March, the wind velocity was very constant, they are approximately independent of the effect of the wind. The figures are, however, dependent on the variations in percentage humidity, though, fortunately, these variations are also of such small amount that the curves obtained are well calculated to exhibit the variation in the amount of ablation caused by temperature alone.

TABLE VIII.

Date.	Vapour Press (observed).	Air Temperature.	Humidity.	Wind Velocity.	Evaporation.
	mms.	° C.	Per cent.	metres/sec.	mms. in shade.
1902—					
December	2·9	− 2·01	73	4·39	1·33
1903—					
January	3·6	− 0·87	80	5·06	0·98
February	2·7	− 3·55	76	7·48	0·84
March	1·5	−11·42	75	13·65	0·61
April	1·2	−14·24	69	8·44	0·40
May	0·9	−19·39	63	6·48	0·23
June	0·6	−21·32	63	6·24	0·14
July	1·1	−17·27	58	8·42	0·36
August	1·1	−15·84	61	8·98	0·64
September ...	1·1	−17·04	77	7·65	0·44
October	2·2	− 6·36	73	6·61	1·16
November... ...	2·2	− 1·30	73	5·10	2·34

It will be seen from Table VIII that the total amount of ablation in the shade during the course of a year was only 9.47 mm. and that, of this amount, 77 per cent. took place in the six summer months, the mean temperature during these months being −4·6° C. as opposed to −17·5° C. in the six winter months.

Definite evidence of the effect of the temperature on the amount of ablation is furnished by our stray observations during the summer. It has been noticed, for instance, that, on the return from summer sledging, certain lakes which had no stream inlet, and which, therefore, during our absence, could have allowed no thaw water to escape, had lost 3 or 4 inches from their upper surface whilst we were away, whereas, during the remainder of the year, only an inch or so had been removed.

There can be little doubt that a considerable portion of the greatly increased loss during the summer months is due to direct radiation from the sun after his return and some of this loss must take place by evaporation from the liquid phase. Stakes imbedded in the lake surface before our departure, in order to obtain a more accurate measurement of the amount of this ablation, invariably met an unfortunate fate. The higher temperature brought about by re-radiation from the wood caused the ice in which they stood to be removed, either by melting or by increased evaporation, with the result that the measuring stake soon assumed a horizontal position.*

It must be remembered that the amount of ablation at any temperature depends not only on the absolute temperature of the air, but also on its relative humidity, since this controls the capacity of the air to take up vapour. Such data as we have on the subject, however, lead us to conclude that the percentage humidity of the atmosphere does not vary greatly during the course of the year. This is well shown in Table VIII, in which Nordenskjöld's results display remarkable uniformity. Little variation was also apparent in the observations at Framheim made by Amundsen.

It must not be forgotten that the temperature of the ice itself is also of importance. The latter need not be at the same temperature as the air—indeed, usually, thanks to the effect of radiation and of other factors of less importance, it is different. It would seem, in fact, as if one factor controlling the ablation must be the difference between the saturation vapour pressure of the ice at its own temperature, and the vapour pressure existing in the air above.† In any case it is certain that the difference in temperature between the air and the ice has a most decided effect on the amount of the latter removed as vapour, and that the greatest ablation will be when the temperature is highest and the vapour pressure difference between the ice and the air is greatest.

Radiation from the Sun.

The chief factors consistently acting towards the production of a difference of temperature between the ice and the air are radiation, reflection, absorption and conductivity of the surface, and it is with the combined effect of these four that we have now to deal. The air is little heated by the passage through it of direct radiation and the temperature of the ice surface is raised relatively to that of the atmosphere by :—

(1) A greater radiation from the sun.
(2) A smaller amount of reflection from the surface of the ice or snow.
(3) A greater coefficient of absorption of the radiation in the ice.
(4) A lower heat conductivity in the ice or snow.

* Measurements made by us at Cape Evans during the winter, though very inexact, showed that the surface of Skua Lake was lowered at an average rate of 2 mm. per month.

† Compare the formula of Weilenmann and Stelling derived for evaporation from water surfaces. (Hann, *Lehrbuch der Meteorologie*, 3rd edition, p. 214.)

$$E = (cb + kw)\ (p_s - p_o)$$

where c and k are constants,

b the barometric height,

w the wind velocity,

p_s and p the saturation vapour pressures at water surface and in the free air above the surface.

The first factor is greatest in the middle of summer, when the temperature is high. Reflectivity also is least in summer when the sun is highest, for at that time the amount of radiation entering the ice without reflection is greatest. The third factor must depend to a considerable extent on the internal structure of the ice: for example, on the amount of included air, and more particularly on the amount of dust, silt, etc., which are contained in the ice, and which have a high intrinsic coefficient of absorption. The fourth is also of prime importance, and depends notably on the density of the snow covering over the ice (see Appendix, p. 473).

The relative importance of these different factors in promoting ablation in the Antarctic is difficult to estimate.

Evidence that the effect due to radiation is not small is afforded by the results shown in Table IX which displays the difference between the amount of the

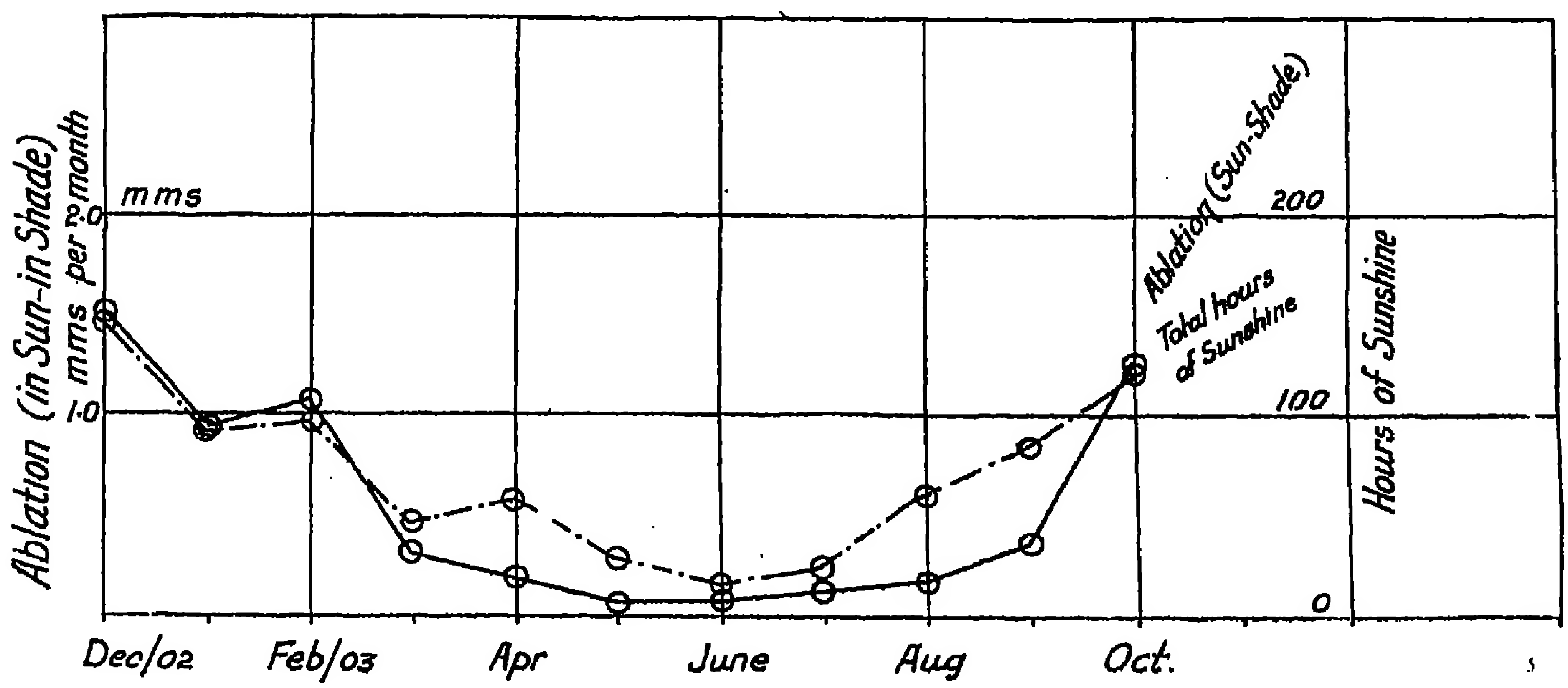


Fig. 93.

ablation from an ice surface contained in a metal dish placed in the sun, and that from a similar ice surface kept in the shade and therefore shielded from a considerable portion of the sun's radiation. In this table, which contains the data collected by Nordenskjöld in 1902–3, the number of hours sunshine is also put down, so that the difference in ablation may be considered in direct relation with the number of hours during which radiation from the sun was effective.

In Fig. 93, these two quantities are plotted so as to exhibit the relation between them in a graphic manner. It will be apparent how closely they follow one another. The relative positions of the curves also make it clear that the agreement would be still closer if due account were taken of the increased intensity of radiation during summer.

That the effect on ablation of the amount of reflection from the surface is not negligible is hardly to be doubted, but, as this second factor is dependent not only upon the exposure of the surface but also on the altitude of the sun, the result of its action is usually completely masked.

TABLE IX.

Date.	Difference in evaporation.	Vapour pressure.	Temperature.	Sunshine.
	mms. sun-shade.	mms.	° C.	Hours.
1902—				
December	1·50	2·9	− 2·01	147·50
1903—				
January	0·92	3·6	− 0·87	89·95
February	1·07	2·7	− 3·55	96·05
March	0·29	1·5	−11·42	44·60
April	0·18	1·2	−14·24	57·30
May	0·05	0·9	−19·39	27·40
June	0·06	0·6	−21·32	14·05
July	0·10	1·1	−17·27	20·20
August	0·17	1·1	−15·84	58·75
September...	0·33	1·1	−17·04	72·80
October	1·26	2·2	− 6·36	119·70

The amount of radiation received per square centimetre on a horizontal surface and, therefore, the amount available for heating that surface is $S \sin A$, where S is the radiation received on a surface placed perpendicular to the sun's rays, and A is the altitude of the sun. If the surface is not level, the value of A is measured between the surface of the ice and the direction of the sun's rays. The ablation effect is therefore greatest when the surface is normal to the sun's rays.

Since also the amount of radiation reaching the earth's surface is greatest when its path through the atmosphere is least, the maximum ablation effect will be on a surface facing north, and standing perpendicular to the sun's rays when he has reached his maximum altitude in summer. This maximum altitude is about 28 degrees in the latitude of the Beardmore Glacier, on the Ferrar Glacier it is 35 degrees, while of course it reaches 90 degrees in tropical regions.

We should thus expect to find that, in tropical regions, the greatest ablation occurs on level surfaces, while, on the Ferrar Glacier, the surface of greatest ablation should slope from the north at an angle of about 55 degrees to the horizontal. We have here, therefore, a factor in ablation which is able to weather Antarctic ice surfaces in forms which may be quite different to those found in tropical or temperate latitudes.

We cannot state that evidence points conclusively to an approximation of ice slopes to any definite angle in the Antarctic; and this is not to be expected, indeed, for the sun during the day is constant neither in direction nor in altitude. We can, however, state that the amount of weathering on ice slopes facing north is found to be considerably greater than that on slopes with a southern exposure—the exceptions being cases when radiation phenomena are complicated by the near presence of black rock.

A good example of the difference between ablation on surfaces facing in these two directions is furnished by an observation made in January, 1911, on the lower, snow-covered part of the Ferrar Glacier. Here, on the upward journey on January 30, the snow had been fairly soft, and the sledge-runners had sunk in to a depth of

about 3 inches—the groove thus made running approximately east and west. On our return 13 days later, we crossed our outward tracks, and it was noted that ablation on the southern wall of the depression made by each runner had proceeded to a depth of over 2 inches, while on the northern side it had eaten in no more than $\frac{1}{4}$ inch. On the level bottom of the tracks, the packed snow had in this interval turned almost completely to ice (Fig. 94).

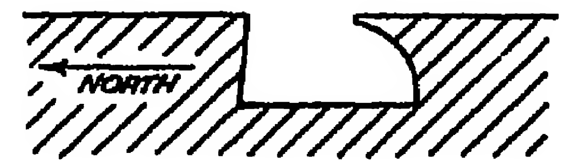


Fig. 94.

Let us now consider the general effect of the sun in weathering a glacier ice surface. On this surface there will originally exist small inequalities or depressions. These may be possibly the ripple-marks left by the wind on the original snow surface, or ablation ripples of similar form resulting from the etching action of the wind on the ice itself during the winter. In these depressions, the sun will act at any time with greatest force on those parts of the ice whose surfaces lie most nearly perpendicular to his rays. This action will first become operative on the return of the sun, and will at that time take effect chiefly on the more vertical portions of the depression, so that the first result is a widening of the depression without corresponding deepening. As the middle of summer approaches, widening and deepening are both effected, but, though the disproportionality between the two becomes less, the deepening effect of the ablation is always less than the widening effect, even with the sun at his maximum altitude.

At midsummer, the ablation effect is greatest, but it continues with lessening vigour until the sun appears for the last time in the autumn.

It results from this action of the sun that the surface of all glacier or pond ice is covered in the summer with shallow pits, which are in general from 2 to 4 inches deep, and up to 1 foot in diameter. The section of the pit varies somewhat, and this variation is dependent on the time of observation and on the intrinsic intensity of the radiation. In general, however, the section in a vertical plane is somewhat as in Fig. 95 (Plate CLXXIX).

It is no doubt due to the slightness of the variation in the sun's altitude during the 24 hours that, in general, the pits are circular, and that no notable difference in appearance is to be seen between their northern and southern sides. This form of ablation mark was called "Thumb-print Ice," since it resembled nothing so much as a number of impressions made with a giant thumb in a soft substance such as plasticine.

Fig. 95.

Fig. 96.

It is clear that, if the original depressions lie sufficiently close together, the pits will grow during the summer until they overlap, and they will then form a modified thumb-print surface in which the edges are sharp and very unpleasant underfoot.*

Such a surface is shown diagrammatically in Fig. 96 and in Plate CLXXX.

* 'Shackleton Geological Memoir,' p. 162. These pits formed from wind-ripples or waves have a length of three to seven times their width.

Where we have met surfaces of this latter type, the pits have invariably been much deeper and narrower than the Thumb-print Ice, and it seems probable that, in such cases, the form is caused by the subsequent action of water on the wind-ablation ripples originally formed on the ice during the winter and spring. The actual production of similar depressions was well observed by one of the writers on the Ferrar Glacier in 1908, when ablation ripples were deepened into sharp-crested waves separated by troughs 2 or 3 inches deep. The whole change took place in a single thaw period of less than 48 hours and was in this case mainly due to water action.

Still other forms occur on slopes that are not horizontal. Thus, at the end of the Taylor Glacier, there occur a number of channels some dozens of feet wide, with vertical walls 20 feet in height on their southern sides. In summer, small streams flow at the bottom of these channels, and these streams carry small quantities of silt. Radiation, by the time of our visit, had caused a disarticulation of the ice grains at the side of the channels, so that they appeared white by reflected light. Although the general slope of their sides approached the vertical, they were covered by February, 1911, with small pits, whose mean depth was about 1 inch, and mean width about 2 inches (Fig. 97).

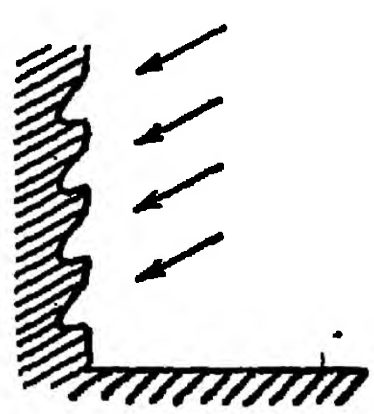


Fig. 97.

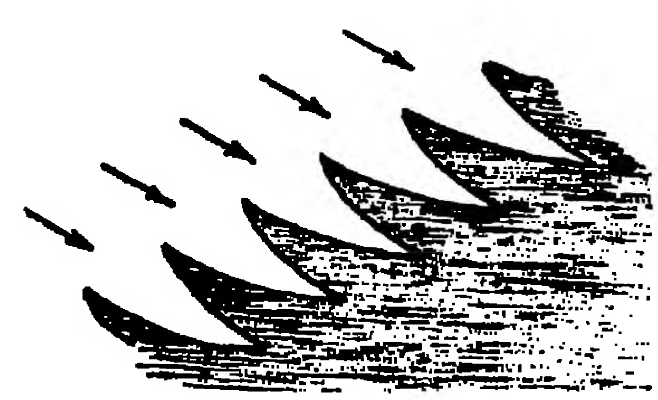


Fig. 98.

The mouths of these pits were approximately oval in vertical section, but the pits were not symmetrical. From the shape of the holes, there could be no doubt they had been caused by radiation from the sun at maximum altitude near noon.

Still stranger, and—from a sledging point of view—more unpleasant, forms were met elsewhere, notably on the Koettlitz Glacier, where the fantastic unevenness of the glacier surface gives the type of modification depending on the angle of incidence of the sun's rays full scope for its development. This form of ablation mark, to which the most polite term applied during sledging was "Ploughshare-Ice," is best developed on the huge ice bastions of that glacier, on slopes of about 30 degrees facing the north. In these places, the general form of the ice shades the northern slope from the sun during that half of the 24 hours when the sun is at its lowest. The sun's altitude, therefore, when it is effective in promoting ablation on the northern sides, varies within narrow limits, and the "ploughshares" are in consequence of very definite shape (Fig. 98 and Plates CLXXXI and CLXXXII).

The depth of the pits was about 8 inches, and the distance from lip to lip was about 8 inches. The mouths of the pits were from 1 to 3 feet wide, and the tongues or lips were quite sharp. The whole pit sloped backward. The ensemble was very unpleasant to the traveller, since the only possible positions in which the foot could be set were within

the pits themselves, and these pits were at such a distance apart that steps of very uneven length had to be made. A somewhat similar effect is experienced when one walks along the sleepers of a railway track, these being so arranged that three of them cover the space of two paces.

Of great importance in modifying ablation processes is the actual amount of the sun's radiation which is absorbed by the top layers of the ice. The temperature difference between the air and the ice naturally depends largely upon this; and it is the difference between the air temperature and the temperature at the upper surface of the ice (not that in its interior) which is so effective in promoting ablation.* It is the variation of absorption with depth which is here most important, since it is rise of temperature and vapour pressure of the surface which has the greatest result in increasing ablation. This point is treated later in this chapter.

Ablation as a Function of the Wind Velocity.

It has been stated that the amount of ablation depends on the vapour pressure just at the surface of the ice (which in its turn is dependent upon the surface temperature), as well as on the relative humidity of the air, a factor which defines its capacity for taking up moisture. Another factor of great importance in promoting ablation is wind.

When we consider that unsaturated air at rest above the ice surface must quickly become saturated in those layers touching the surface, it is quite evident that any agent which assists in mixing the lower layers of the atmosphere will also be effective in modifying ablation. If we exclude the slow process of diffusion, this mixing of the different layers can take place in one of two ways :—

(1) By vertical currents caused by the heating and consequent expansion and upward movement of the air in contact with the ice, and
(2) By a wind of sufficient velocity to cause increased turbulence in the lowermost strata of the air.

Of those two factors the first is undoubtedly effective locally, and when it does occur it is assisted by the much greater vapour pressure due to the higher temperature of the ice. As the heating of the ice is undoubtedly greatest in the vicinity of silt or rock, it is in these places we should expect the effect to be greatest.

The second factor is, however, of even greater importance in promoting ablation. Even with the smoothest ice surfaces, the mixing of the air-layers must be considerable for quite small wind velocities, as is clear from the formation of eddy drifts and of ripple-mark sastrugi on snow surfaces. Side by side with this increased evaporation in strong

* The quick change of snow to ice in a surface drift is clearly associated in considerable measure with high temperature due to the low heat conductivity of such snow-drifts. The same factor will equally lead to greater ablation from snow than from ice surfaces. Generally speaking, those conditions which lead to accelerated growth in mean size of glacier grain are conditions which promote increased ablation.

winds occurs the purely mechanical* action of the drift it carries, and, in the majority of cases, it is extremely difficult to separate the effects of the two.

TABLE X.

Velocity, miles per day.	Mean wind velocity.	Temperature.	Average change in weight per day. Ice surface 56 sq. cms.
		° F.	Grams.
000–200	112	−24·4	+0·067
200–400	303	−22·9	−0·211
400–600	452	−15·8	−0·519
600–800	642	−16·5	−1·577

Table X, compiled from the meteorological data available, exhibits very well the importance of the rôle played by the wind in ablation processes during the winter. To express these results graphically, the loss in weight per day from a surface 56 square centimetres in area is plotted in Fig. 99 against the total number of miles of wind registered during the period at Cape Evans. It will be seen that the amount of ablation increased very much faster than the wind velocity. In fact, it increased more or less in proportion to the square of the velocity, as is shown in the dotted curve.†

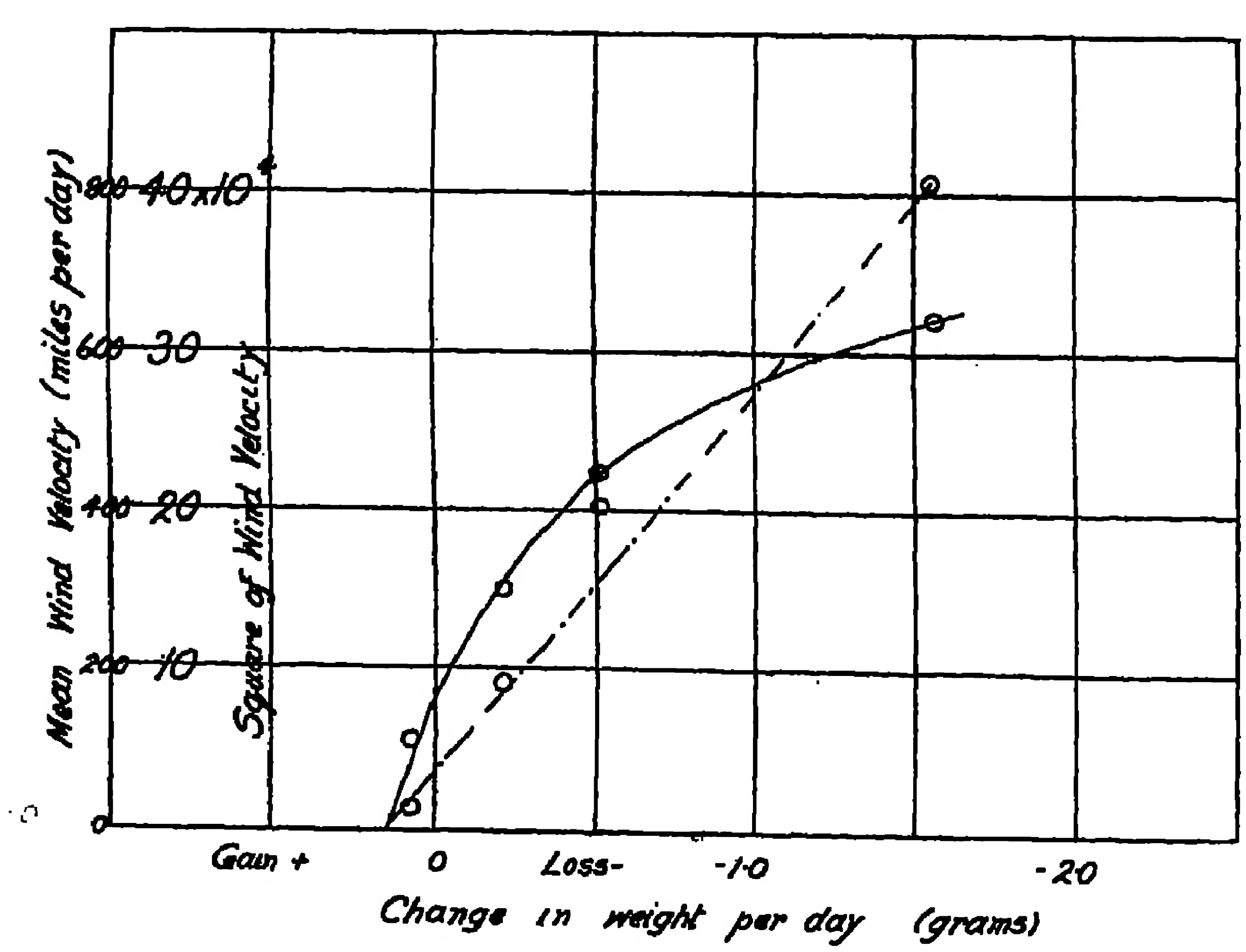


Fig. 99.

All the observations made at Cape Evans in 1911‡ have been used in compiling Table X. These have been grouped according to the total air displacement during the day, and the mean value of the ablation has been plotted against the mean air

* The term "mechanical action" includes the action of drift and foreign matter in breaking off portions of the surface as well as that action due to absorption by the surface of the kinetic energy of the flying particles. As pointed out in Chapter IV, this absorption of energy increases the number of "mobile" molecules present in the ice, and also the number of molecules capable of passing the ice boundary into air.

† It is possible that the relation brought out in Fig. 99 may require slight modification, when the sum of the hourly values of the square of the wind velocity is substituted for the square of the mean daily velocity, *i.e.* when $\int_{h=o}^{h=24} (V_h)^2$ is substituted for $\left(\int_{h=o}^{h=24} V_h\right)^2 = V_d^2$, where V_h represents the hourly velocity and $V_d =$ total number of miles in the day.

‡ Observations were confined to the winter months.

displacement in the full curve. Thus the number 112 miles in the day is the mean value of all the observations from 0 to 200 miles, and so on in steps of 200 miles.

Above 800 miles the observations numbered only three, and were therefore neglected.

The observations here cited were made at Cape Evans during the first winter, while the sun was continuously below the horizon, so that direct radiation from the sun was here inoperative. The temperature was always low, though by no means constant, and the humidity was not measured. It must be remembered that high wind velocity is generally associated with high temperatures.

A study of Table X reveals another point of considerable interest, namely, that for low wind velocities the ablation is a negative quantity; that is to say, under these conditions, deposition rather than denudation takes place. This is due to the low temperature and excessive radiation from the earth in calm weather, causing deposition of crystals on the ice surface.

From the table it seems clear that the ablation does increase significantly with increase of wind velocity and air temperature, but part of this increase may well be due to a greater dryness of the strong winds, this dryness being brought about by the forced descent of air near the place of observation.

In fact, the erosional effect of wind (physical plus mechanical) is large. This is borne out by the observations already cited when discussing sastrugi of erosion, and, though the facts observed and described relate only to snow surfaces, they are to some extent applicable to ice surfaces, and ripple marks have been observed on ice surfaces which were clearly due to wind action alone. Certain of the snow surfaces with sastrugi of erosion are, in fact, quite comparable in hardness with some ice surfaces, and it is quite common to find snow-drifts compacted to such a degree that it is almost impossible to use a spade for digging out the blocks of snow.

That the mechanical effects of wind are at times considerable will be more easily understood, when it is stated that, in some of the heavy blizzards at Cape Evans and Cape Adare, pebbles weighing about 4 or 5 grams were picked up from the ground and hurled through the air with such velocity as to constitute a menace to the windows of the hut, and to break thermometer stems at a height of 3 or 4 feet above the ground. At the end of the first winter, the sea ice in the lee of Cape Evans was sprinkled for some 300 yards from the shore with small pebbles up to 1 centimetre in diameter, which had been blown from the Cape. As the velocity during transit of these pebbles was undoubtedly many feet a second, it will readily be seen that they were capable of doing a considerable amount of erosion, though this amount is not comparable with that which is accomplished by the constant stream of the much lighter ice crystals which are carried by the wind in the form of drift. It is to be expected that by far the greatest amount of this type of ablation will take place in positions where the wind is strongest—that is, on projections above the general level of the surface.

This is, indeed, the case, for the most striking example of ablation we have met in the Antarctic is to be referred mainly to this cause. The observation in question

was made by the Northern Party in the latter portion of the winter and in the early spring of 1911, when both sun and temperature were still low, so that temperature effects must have been small and thaw non-existent. On their first sledge journey at the end of July, an area seamed with ridges of spiky pressure composed of small pieces of ice 3 or 4 inches thick gave them considerable trouble, and, in spite of all precautions, capsized the sledge several times. The almost complete disappearance of this pressure ice brought about by the agency of ablation and drift-chiselling is described in some detail on p. 365 of the chapter on Fast-Ice.

More striking, however, in that the cause of the ablation is more definitely marked, is an observation also made at Cape Adare, where, during the blizzard lasting from May 4–14, many blocks of ice on the icefoot were eroded to the extent of 2 inches on the windward side, while only a fraction of an inch had been removed from the leeward side. This observation was made possible by the fact that the boulders of ice here resting on the icefoot were all covered with a 2-inch layer of frozen spray, which was easily distinguished from the underlying mass, owing to its different crystalline structure. At this time the temperature was low, and the sun was below the horizon for the greater portion of the day, so that, without doubt, the major part of this ablation was due to the effects of the high wind. (For illustration, see Fig. 135, Chapter IX.)

It was, in fact, quite common to find ablation most effective on the windward side of such boulders, and this was most easily and best seen where the ice contained silt-bands, the ablation then being emphasized by the weathering out of the grains of sand on the windward side of the blocks.

These show up after weathering as projecting grains or ridges arranged, in general, in beds or lines, while on the lee side of the block of ice the sand grains do not project but are wholly included in the body of the ice (Plates CLXXXIII and CLXXXIV).

Other striking examples of the amount of ablation due to wind action are furnished by the weathering out, during the absence of the sun in the winter months, of the masses of alga embedded in some of the lakes at Cape Evans and Cape Royds. At the conclusion of the winter, these pieces of alga stood out above the general level of the lake surface as much as 2 inches.

More convincing still is an example hailing from Inexpressible Island. Here, at the beginning of the winter, a seal was killed on the icefoot, and as the warm blood flowed out it sank into the ice, forming a compact reddish mass. Three months later, this mixture stood up a full 2 inches above the general icefoot level. This instance is particularly interesting, as the effect of direct radiation from the sun was betrayed immediately it became powerful enough, when the dark mass of seal's blood and ice melted, and once more became level with the ice surface (Fig. 111, Chapter IX).

The ablation ripples, which form at times on ice surfaces such as ponds and glacier ice, are often evidently a direct result of wind action. These have exactly the same form and size as the similar ripple-mark sastrugi formed on snow surfaces, and they are about 1 inch deep and some 2 inches from crest to crest. In the winter they develop quite slowly on the surfaces of most of the fresh-water lakes, and are quite well marked

on the return of the sun in the following spring. They develop much more quickly during the summer months.

A very good example of these ablation ripples was seen by one of us on the Ferrar Glacier in 1908, and described in the 'Shackleton Geological Memoir' (p. 92). Here ripples in all stages of development were visible at one time, owing to the progressive removal of the snow-drifts on the glacier surface by the agency of the wind.

Finally, actual comparative measurements on the difference between the loss from ice-blocks placed in the open, and from similar ones sheltered from the wind, show that in the former case the loss in weight is from 2 to 5 times that which takes place from the blocks sheltered from the wind.

The Effect of Salt Included in Ice.

Comparative observations on the amount of ablation from samples of sea ice and similar samples of fresh ice, showed that the ablation from the sea ice was in general slightly greater than that from the sample of fresh-water ice, but notable exceptions to this are the result of exposure to drift at comparatively high temperatures. At temperatures which are above the cryohydric temperature of some of the salts in the sea ice, the ice becomes wet and sticky, and the snow which impinges against it sticks, and may increase the weight of the block considerably.

The results show that, though this increase to the surface is at times considerable, the final result at the end of long periods is almost the same as for blocks of fresh ice hung under similar conditions. From this it seems clear that ablation from the upper surface of sea ice should proceed (*cet. par.*) at about the same rate as it does from the surface of a glacier. Actually, the loss from the sea ice surface will in general be greater than that from a surface of fresh ice, owing to the fact that the former is heated by conduction from the warm sea below.

Experiments with salt-water ice are complicated by the draining of the salt from the block after it is suspended in the air. This draining effect should also be considered in dealing with the ablation from all naturally raised surfaces of sea ice, whether pressure blocks, or areas which are raised above the sea level by their thickness alone. Because of this action, in fact, all old raised surfaces of sea ice may be dealt with, as regards ablation, to all intents and purposes as if they were made of fresh ice.

The Effect of Exposure and Environment.

From what has been said previously, it will be recognised that the amount of ablation at any position is largely dependent on the exposure of the ice surface, that is, its height above the general level, its slope, its texture, and especially its position relative to sand or rock in the vicinity.

A concrete example is furnished by a consideration of the grit-laden ice which is to be found in many places on Antarctic glaciers. In the presence of sunlight, the silt in the ice is warmed by absorption of radiant heat from the sun, and the ice in its vicinity

becomes heated, both by direct conduction and also by absorption of the long heat rays re-emitted by the dust particles. It is easy to see that, in such cases, the amount of heating of the surface layers is dependent on the amount of silt in the upper layers of the ice, so that ice containing a high percentage of silt will be hotter on the surface, and therefore will be more ablated than ice in a similar situation but with a lesser percentage of included dust.

Definite figures for the magnitude of this effect are, however, not easily given, chiefly because silt-bearing layers, where the denudation is due definitely to ablation and not to thaw, have not been studied in comparison with adjacent areas of perfectly clear ice. In our experience, in fact, it seems clear that ablation will generally be accompanied by thaw wherever the dust particles are sufficiently large to have sunk into the ice. Wherever, therefore, the particles are as large as, or larger than, sand-grains, the effect of ablation will be masked by that of thaw. The single definite example we have noted, where the required conditions are fulfilled, was on the north side of the Ferrar Glacier, near the centre of the Kukri Hills. Here, three or four long parallel lines of clay-coloured ice, about 2 inches in width, were observed running parallel to the side of the glacier. On February 9, in 1911, it was found that the surface of this discoloured ice was depressed about 2 inches below that of the contiguous clear ice. Even in this case, we have unfortunately no evidence as to how long ablation had acted in lowering the surface by this amount, but it seems clear that the depression must have occurred since the winter. It is thus impossible to give a numerical value for the additional ablation caused by such inclusions, though there can be no doubt that a small amount of silt in the ice has a most important effect.

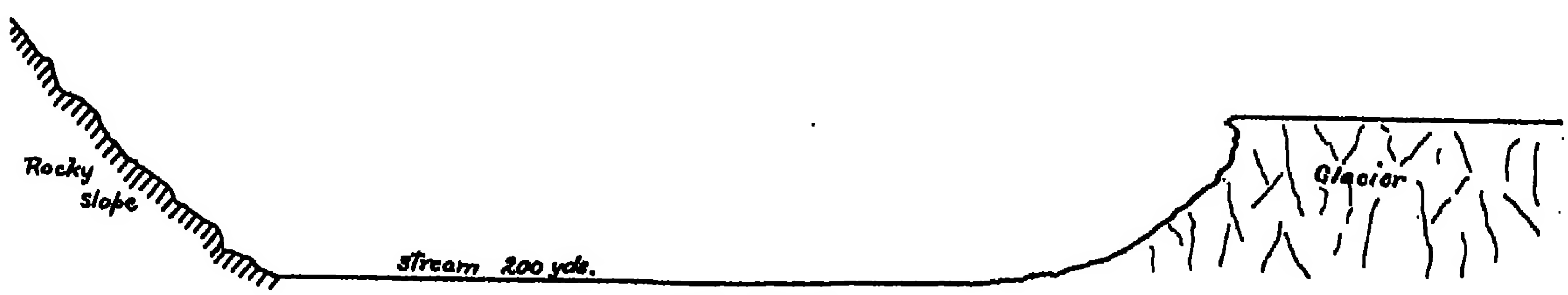
Further examples of the effect of radiation absorbed by rock particles in the mass of the ice, are furnished by the horizontal silt bands in the terminal walls of Antarctic glaciers. Though the effect is most marked when thaw-water is formed, it is none the less clear from observations made where clear and silty ice are contiguous to one another, and where the rays of the sun are able to fall upon the ice, that the amount of ablation is much greater from the silty ice than where the ice is clear and free from silt. For instance, as early as September, 1911, before any signs of thaw had been seen, it was observed by the Northern Party that a sprinkling of dust had fallen from the face of the silt bands which cropped out on the face of Warning Glacier, while the ice of some of these discoloured bands had been ablated some half-inch deeper than that of the clear bands on either side of them. Similar examples are not wanting from the neighbourhood of Cape Evans, but the effect was less pronounced.

A similar result is due to the occurrence of isolated rock masses on or in the body of the glacier. Rocks and other dark objects absorb almost all of the incident radiation from the sun; in consequence, their temperature is raised sometimes many degrees, and they then cause a general warming of the air by convection currents. A much more effective result of this local heating, however, is the re-emission of radiation in the form of rays of greater wave-length than those incident upon it, that is, in the form of heat waves. These waves, being easily absorbed by the ice, have a very considerable effect

in raising its temperature; and this rise of temperature is accompanied by a corresponding increase of vapour pressure.

The importance of this effect in promoting ablation, like that of many other factors, is difficult to estimate. In Victoria Land, at least, the absorption in the middle of summer, in the immediate vicinity of the rock, is so strongly marked, and the temperature of the ice is raised to such an extent, that thaw sets in and masks the phenomena due to true ablation. At some distance away from the exposure of rock on the other hand, the effect, though it may still be quite intense, cannot be detected, since there is usually no ice unaffected by the radiation to enable comparisons to be made. The effect on ice of this re-emitted heat radiation decreases quickly as the distance from a small object increases, and will therefore be quite local in character (Plate CLXXXV).

The order of magnitude of the effect is well seen by the occurrence of what we have called radiation gullies at the sides of nearly all the valley glaciers we have seen in the south. Such a lateral gully is particularly well developed on the Ferrar Glacier, where it flows past the Kukri Hills close to the Cavendish Falls. Here it reaches a depth of fully 100 feet. It is shown in section in Fig. 100, which is drawn approximately to scale, and shows the slopes on the glacier side of the gully. There is no doubt that



1 inch = 100 feet.

Fig. 100.

both thaw and ablation are effective in this place, the effect of the former being betrayed by the stream at the bottom of the gully, though the absence of the vertical grooving which is invariably seen where water runs down the face of an ice-cliff (Plates CLXXXVI and CLXXXVII), seems conclusive evidence that ablation is the more effective of the two agencies in removing the upper portions of the glacier ice. Plate CLXXXVIII shows a radiation gully round a nunatak in the Ross Island Highland-Ice sheet. The radiation gully at the side of Buckley Island, at the top of the Beardmore Glacier, is another example from higher latitudes (85° S.).

Though the lateral gullies are at times well developed in temperate regions, they do not there appear usually to have such steep slopes. This may well be accounted for when we consider that in those regions thaw plays a much more important part as an agency of denudation; and, moreover, the amount of rock lying on the glaciers is generally much greater than is the case in the Antarctic. Both these factors tend to prevent the formation of well-defined radiation gullies, just as they prevent the formation of the wall side and wall termination so characteristic of Antarctic glaciers.

Examples of the truly enormous effect exerted by the presence of rock, in modifying the originally uniform surface of a glacier, might be multiplied indefinitely, for this

modification occurs, not only by the bank of the glacier, but also in the vicinity of any moraines, isolated rocks, or even grains of sand, lying on the glacier surface. This effect is especially well shown by the huge longitudinal depressions which, on certain glaciers, are the only remaining evidences of the former occurrence of scattered surface moraines, and also by the sporadic occurrence in these valleys and on the general glacier surface, of cryoconite holes similar to those described by Drygalski from the Greenland glaciers.

These phenomena will be treated further, under the following section headed "Thaw," since the presence of rocks has often so great a heating effect upon the ice that its temperature rises above freezing-point and water is formed.

Cases have, however, been seen where the presence of rock has notably increased the ablation without inducing thaw, and these examples are best seen in the early spring, when the temperature is still well below zero Fahrenheit. Thus, on every lake at this time, significant depressions may be observed to surround all rocks lying on the surface, bits of seaweed frozen into the lake, or stakes put in to mark the ablation from the surface. By the end of September, these depressions round the ablation stakes may have extended to a distance of 1½ inches from the stake, and may be in places as much as 2 inches deep.

Thaw.

Thaw occurs on a clear surface of ice or snow only locally, and at very infrequent intervals, even in the middle of a normal Antarctic summer. In addition, since the necessary high temperature can extend only to a very slight depth, it is clear that the formation of thaw-water occurs near the surface only, the extreme cases being where the presence of silt and boulders embedded in the ice only a short distance below the surface may cause a local heating. It is, indeed, the general rule that the lakes in summer thaw out first round their edge, leaving in the centre an isolated mass of ice, which is commonly frozen to the bottom of the lake, the exceptions being the small and shallow lakes where melting takes place from the bottom as well as from the sides. During the first Western Journey, one lake was found below the Taylor Glacier in Dry Valley, the greater portion of which still remained frozen in February, the solid core being surrounded on all sides by a strip of water several yards wide.

Subterranean melting occurs also in the shallow snow-drifts which are formed in the lee of small rock prominences, and small streams may be seen at times in summer issuing from the lower portions of these. The thaw-water which forms these rivulets is caused by the melting of those parts of the drift in contact, or nearly in contact, with the ground; and this melting may take place to a considerable extent while the upper portion of the drift remains in the usual form of cold, dry, powdery snow.

If a series of warm, windless, clear days occurs, however, thaw on a clear ice surface may take place, though this favourable conjunction of circumstances is seen but seldom. It is certain, indeed, that summers do occur in which large areas free from rock are *entirely* unaffected by thaw, and thaw on the Ross Barrier must be a most infrequent

occurrence. When, however, an Antarctic thaw does take place, one is astounded by the vastness of the effect brought about by an apparently small change in the meteorological conditions.

This is particularly striking on a large glacier, such as the Ferrar. The first effect of a thaw which becomes noticeable is a faint sizzling sound coming from the surface, as the bubbles of air which have been held under pressure in the ice are melted out and escape through the film of water which covers the glacier. The thaw-water formed in this way naturally flows along the ablation depressions or ripple-marks and causes these to deepen and join up to form channels down which miniature streamlets begin to flow. In parts of the glacier where these streamlets originate, the channels are about 4 inches deep and only a few inches wide, and they may be so numerous that the greater portion of the surface of the glacier is bathed in water. On their downward way these first threads of water join in large numbers to form wider streams (Plate CLXXXIX). These larger surface streams, though at times of considerable width, are only a foot or two deep; and this comparative shallowness seems to be a characteristic of all thaw streams on Antarctic glacier surfaces.

In the upper reaches of the glacier, these streams have a tendency to flow towards the lateral radiation gullies at the sides of the glaciers, particularly towards the northern side. In these gullies, the sum of all the small streams totals up to quite a large body of water, and streams have been observed in them which, when still 20 miles or more above the glacier termination, had a width of 200 feet and a maximum depth of 4 or 5 feet, while their stream velocity sometimes reached 6 miles an hour.*

On any of the few days when thaw is at its maximum, a rough estimate of the amount of water issuing from the Ferrar or the Koettlitz Glacier at sea level leads us to believe that the volume of water flowing down over the surface is about 1000 cubic feet per second for each mile of the glacier's width.

This is of course quite an exceptional figure, and we have every reason to believe that no other outlet glaciers in the districts which have come under our notice rival the output of thaw-water from these peculiarly favoured regions. For instance, in the year when the greatest amount of thaw which has yet been seen was recorded from the Ferrar Glacier, the Beardmore Glacier was practically free from running water, so far as could be seen by a sledge party which traversed it twice from head to foot in the height of summer.† No flowing water whatever was seen on the Beardmore Glacier in the summer 1911–12.

One of the most amazing aspects of the occurrence of thaw-water is the extraordinary variability in amount which is displayed. There is of course no flow of water from the beginning of April until the end of October. It is not until November, in any normal year, that any water whatever is to be seen in the lateral gullies where it first makes its

* Lieutenant Skelton, the engineer of the "Discovery," measured the output of a single stream on the Ferrar Glacier near Cathedral Rocks. The stream was one of the lesser ones, being 7 feet wide and 9 inches deep. He calculated that 53 tons of water per minute flowed down the glacier in this channel alone. (R. F. Scott, 'Voyage of the "Discovery",' vol. 2, p. 106.)

† Shackleton, 'Heart of the Antarctic.'

appearance, while, by the end of March, the streams are again permanently frozen, and have usually been ice-covered for several weeks before that date. Indeed, if one has happened to be travelling on the glacier surface during an unfavourable summer, or only during the colder portions of the year, it will be difficult to believe that the glacier holds such potentialities for thaw as are exhibited on such rare occasions as have just been described.

That these possibilities are sometimes realised is now certain, and almost every sledge journey to the west has brought back records of phenomena which show the power of the thaw under favourable weather conditions. The Koettlitz and Ferrar Glaciers, in particular, have afforded a peculiarly striking series of examples, both of actual thaw in progress and of a great variety of ice-forms which could have been carved out in no other manner. It is from our experience on these two glaciers that most of the notes in the present section have been compiled, with occasional reference to glaciers in other parts of Victoria Land when these display some aspect of thaw phenomena peculiar to themselves, or to a particular region.

The summer of 1910–11, though possibly not a particularly cold one, was far from being an exceptionally favourable season for thaw; nevertheless, a stream, which had an output of fully 200 cubic feet a second, was still flowing at the beginning of March down the western side of the Koettlitz Glacier. It was, however, through the sculpture of the glacier towards its centre that one was best able to judge of the enormous amount of water which must have been pouring down the surface of the glacier at some period of the summer. Everywhere, on the western half, were seen the relics of streams averaging some 50 feet in width, and in depth certainly 4 feet and possibly more. These stream beds were about 300 yards or so apart; and, though the grade here was not very steep, the stream velocity at periods of maximum thaw must have been quite considerable.

Before the advent of the Western Party, at the beginning of March, these one-time streams had become covered with 4 inches of ice, and had then drained away almost completely until the merest trickle of water was left (see Plates CLXXX and CLXXXI), the ice-covering remaining fixed to the banks in a concave form, being some 2 feet lower in the centre than at the sides.

In the middle of the stream, moreover, where there had been small ice-islands only just submerged, this draining away of the water had lowered the surface of the ice until it rested on the top of the island. The ice above the islands had then remained fixed to their summits, or, where not strong enough to bear its own weight, it had been ruptured over the projection, and a network of cracks had formed in similar fashion to those which form during the winter in the sea ice off a shallow shore.* With further lowering of the ice-covering, this often detached itself from the walls of the channel, and sank to form the type of ice-formation we called "pie-crusts" (Fig. 101).

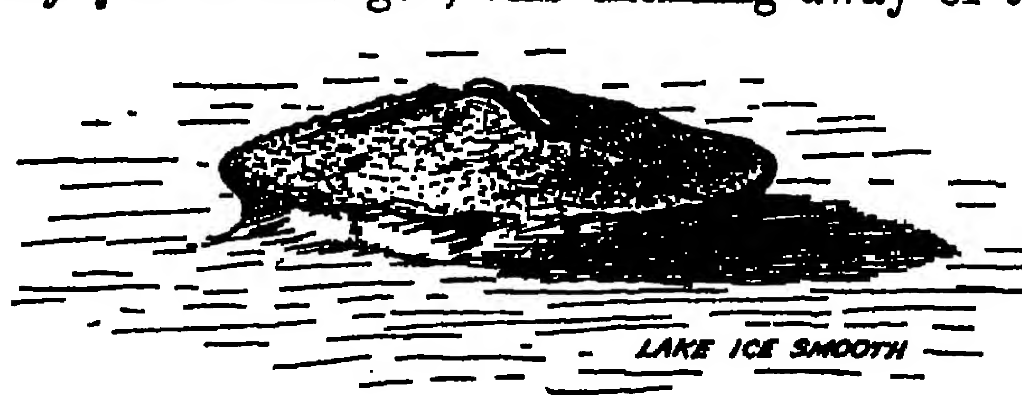


Fig. 101.

* Chapter X, p. 356.

Plates CXC and CXCI give a good idea of the surface of this portion of Koettlitz Glacier.

It may readily be seen from this description that, during the thaw season when the streams have no ice-covering, the surface of a glacier such as the Koettlitz may be practically impassable for sledge parties unless provided with boats or canoes of some kind.

We have thus seen that the thaw-water formed by the melting of a clear ice surface is at times very considerable. Far more effective, however, as we have already stated in the section dealing with "Ablation," is the thaw which occurs in the presence of any dark substance lying on, or close to, the surface of the ice—for instance, rocks, silt, or sand. To this agency must be ascribed the much greater thaw effect which occurs along the sides of the glacier, which is due to radiation from the dark warm rock of the wall of the glacier valley. It is, therefore, clear that the amount of thaw-water developed on any glacier surface will depend largely on the environment of the ice mass and on the amount of moraine material lying on its surface, as well as on the amount of fine rock dust blown on to the ice from the surrounding rock masses. It is fortunate, indeed, from the point of view of the explorer, that the amount of dark material lying on the surface of most Antarctic glaciers is very small, for, if it were otherwise, the glaciers, instead of being difficult to traverse for a short period in summer only, would be almost impassable for the greater portion of the summer, as is now the case with a few debris-covered exceptions.

Mention has already been made of the fact that, in the immediate vicinity of small rock masses, the effect of the rock in raising the temperature of the ice will decrease quickly as the distance from the rock increases. Quite close to it, therefore, the temperature of the ice will rise to freezing-point and thaw-water will be formed. For the case of small particles, such as sand blown on the glacier surface, the melting effect of an aggregation of a few grains only extends in the height of summer to a distance of about 4 inches from them, so that the grains as they sink in the ice form a hole which is not less than 7 inches in diameter. This hole is often partially filled with water in the middle of summer. These cryoconite holes, as they have been called,* do not, however, continue downwards indefinitely. After a certain depth, the intense action of the sun's rays on the sand becomes lessened by the shielding effect of the ice walls on either side, and of the superincumbent water layer. The depth of the cryoconite holes, therefore, reaches a limit when the sinking of the sand grains, under the effect of such radiant heat from the sun and the sky as can reach them, is balanced by the ablation of the clear glacier surface under the total solar radiation. This depth in our latitude was found to be, in the mean, 9 inches for holes with a mean diameter of 7 inches. From this, it is clear that something of the order of 300 cubic inches of ice are caused to melt during the summer by no more than a tenth of a gram of sand. Clearly the melting due to a given small amount of sand will be greater the more evenly distributed it is.

The water in the cryoconite holes becomes frozen at its surface during any spells of cold weather, especially during the later portion of the summer when the sun is lower,

* Drygalski, 'Grönland Expedition,' p. 93.

and the individual crystals of these ice-coverings have a peculiar radial arrangement due to growth proceeding from the sides. This freezing may proceed until the hole is completely filled with a mass of almost transparent ice, with all the air concentrated in the boundaries between the radially-arranged crystals, which thus contrasts strongly with the whitish bubbly ice of the surrounding glacier surface. Quite commonly, however, after the formation of the first surface-ice over the water, a cold spell causes a contraction-crack to form in the glacier ice. This crack may traverse the cryoconite hole so that the water inside drains partly away, leaving an ice sheet an inch or two in thickness with an air-space beneath it. If the water drains away slowly, the next night may see a growth of ice outwards from the cold walls of the hole at the new water-level, and this periodic freezing may continue during several nights. This is the explanation of the curious shape of cryoconite holes sometimes observed. A section of one of these is shown in Fig. 102. It is unusual for the hole to be completely emptied of water, and a sheet of clear ice 2 inches or more in thickness almost invariably lies directly above the grains of sand.

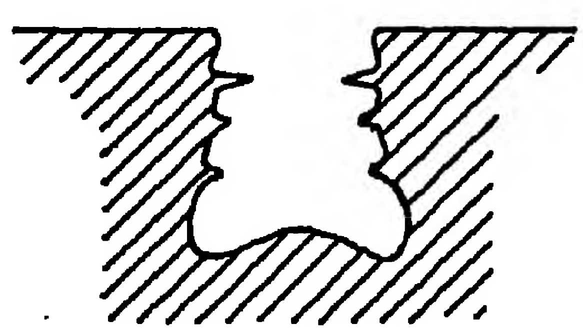


Fig. 102.

Evidence that the deepening of cryoconite pits keeps pace in succeeding years with the lowering of the general glacier surface by ablation is furnished by the great regularity in depth of such holes as have been investigated.*

It is clear, therefore, that this action continues year after year by virtue of the radiation transmitted through the ice above and absorbed by the sand at the bottom of the pits, by which it is again emitted in the form of the longer heat waves which are more easily absorbed by the ice.

From the sequence of events described above it is clear that, on a level surface, the presence of very small sand or rock deposits does not greatly alter the form of the glacier.

Quite a different effect is seen, however, when the surface on which cryoconite pitting takes place is already very irregular and broken up, as in Fig. 103, which represents diagrammatically a slope facing north.

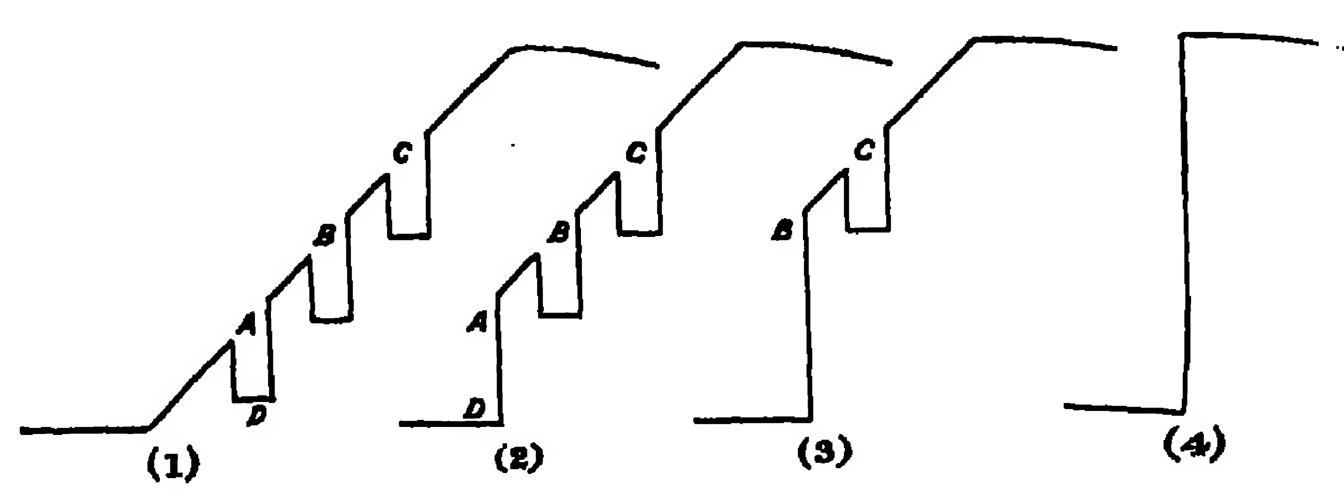


Fig. 103.

The action of the sun's rays is here made more effective by the existing slope, and the first effects will consist in a melting of the ice on the sunny side of A, so that a vertical wall AD is formed on this side. The sun next attacks the cryoconite hole B, and reduces

* The fact that silt in cryoconite holes on a level glacier surface only sinks a short distance into the ice, has already been turned to good account by Nordenskjöld, who has been able to deduce, from the occurrence of a layer of these holes in the body of the Snow Hill Glacier, that the glacier surface was lower than it is at the present time, at some period in the past.

it to the same condition. Later, C is in turn attacked, and the final result is a vertical ice face on the sunny side which is limited in height by the height of the point above the level where the slope was originally horizontal. Thus, on a glacier surface where pressure ridges and blocks of ice occur in the form of waves running about east and west, already honey-combed with cryoconite holes, a few seasons only are sufficient to form steep walls 50 feet or so in height on the northern side of the waves. This form of surface is exceedingly well developed on the western side of the Koettlitz Glacier for a distance of several miles below the Heald Island Nunatak. As the glacier moves slowly forward, the process of weathering continues on the northern side of the ridges; and, after their summits have been denuded away, the height of the walls becomes less and less, until finally, at a point well below Heald Island, an almost level glacier surface is again found, and the only sign of the cycle that has taken place remains in the large quantity of silt which lies in the stream-channels, and in the surface hollows which are carved out on the glacier surface by the weathering agencies.

There can be no doubt whatever that the unusually large amount of thaw-water in the summer on the Koettlitz Glacier owes its origin to the large amount of silt and sand material on the glacier surface and to the undulations formed on passage of the glacier past Heald Island. This is borne out by even the most cursory examination of the glacier. Thus, on the eastern half of the glacier, the occurrence of silt or sand is infrequent, and here the glacier is, comparatively speaking, level and free from surface water. On the western portion of the glacier, which has passed down to the left of Heald Island, however, the condition of affairs is totally different. Here the ice is pitted with cryoconite holes containing sand blown from the land near by. Broken up by its passage between Heald Island and the mainland, the irregularity of surface is pronounced, and the glacier is, in consequence, very strongly affected by the sun, so that the northern side of the bastions melt exceptionally fast, forming an even more irregular surface which is seamed with streams of considerable size (Plate CXCII).

It is to this ability of sand, and particularly scattered moraine, to bury itself in the body of the ice that the poverty of surface medial moraines on Antarctic glaciers is partly due. If one follows down such a moraine from its place of origin, one notices a very instructive sequence of events. First, it will be observed that the amount of material on the surface at the point of formation of the moraine is small—much smaller than that which would be formed in temperate regions. It is, in fact, nearly always what we may call a scattered moraine (Plate CXXXVI). As this scattered moraine moves slowly down the glacier, the individual blocks tend to sink into the ice surface, and to be covered with freshly fallen or drifted snow, and before long all that is to be seen is a number of large isolated angular blocks. This transformation has usually already occurred at a distance of about 2 miles from the place of origin.

One very definite effect of such moraines occurs by virtue of their strong absorption of the solar radiation, and this is shown by the increased ablation in their vicinity (Plate CXLI), an increase so great that it tends to lower the whole surface of the moraine-covered ice to a notable extent. Even if the whole of the moraine material has

already sunk into the ice and disappeared from sight, therefore, the presence of the moraine many miles below the point of origin may still be made evident by a longitudinal depression on the glacier, a groove which is often emphasized by a more or less slight discolouration of the ice due to the products of the frost-weathering of the blocks. The occurrence of such longitudinal depressions on the lower portions of many Antarctic glaciers is often the sole remaining clue of the former presence of medial moraines. They are often only 100 feet in width, but may be 100 yards or more.*

Protective Action of Rock.

Owing to the inequalities of the moraine surface, the larger boulders on it are at times surrounded by drifts of snow which become consolidated into ice, and thus the rocks sink, not only by an actual movement into the ice, but also by an upward growth of ice into the snow of the drifts (Plate CXLII). Such a process as this is frequently seen on medial moraines, and is necessary to explain the disappearance of the largest blocks into the ice mass, since a large mass of rock protects the ice below it from the effects of the radiation from the sun and sky. This protective action is due to the opacity of the rock to radiant heat, combined with a low heat conductivity, so that, though the upper surface of the rock in contact with the air may be heated several degrees above air temperature, this heat does not appreciably conduct through the rock to the ice. The result is, that the portions of the ice directly below the centre of the rock are shielded from direct radiation, and are only affected by certain stray reflected rays. In such cases, the large boulders remain perched on pedestals of ice (Plate CXLV). If these boulders are wide and tabular, the ice column can reach a considerable height. In general, the maximum height is limited by the fact that, the greater it becomes, the greater will be the effect of radiation on the lower portion of the column, since the shielding influence of the rock will only then be effective when the sun's altitude is greatest. The greater the width of the boulder, the higher can be the pedestal upon which it rests; and this explains why large solid rocks are so much more liable to remain on a glacier surface than the small sand grains derived from the surrounding rock masses.

It is, in all probability, to this cause we must attribute the fact that, on the scattered moraines of the upper Ferrar and Taylor Glaciers, all the blocks remaining on the surface are of very considerable size, while there seems to be at the same time a preponderance of the tabular blocks formed of Beacon Sandstone. The lack of "glacier tables" on the lower portion of the Ferrar, on the other hand, is very probably due to a precipitation and drift which more than neutralises ablation.†

From what has been said earlier in the chapter, it might be inferred that the effect of sand resting on ice is always to increase ablation and thaw in the vicinity. In particular cases, however, this is far from true; for, if the layer of morainic material is of sufficient

* The longitudinal grooves leading from Cavendish Falls to the Taylor Valley no doubt mark the presence of former surface moraines.

† This phenomenon of increased snowfall at the lower levels of a glacier is of such general incidence as to leave no doubt that it is a real one common to this sector of Antarctica at least.

thickness—though it may be composed of a number of small stones or even of sand grains —it will protect the ice beneath it from radiation exactly as does a large solid boulder The only difference is, that, in this case, the ice pedestal is so broad that it cannot readily be recognised as such.

Since the protective action of the moraine is dependent on the combined effects of shielding from the sun, and low heat conductivity of the constituent rocks, it is obvious that the action will be more efficient the thicker the moraine deposit.

Such ice-borne moraines can clearly only remain visible if the local deposition is less than the local ablation and thaw, and they are therefore well developed in those places where the erosion is greatest. Examples which show this particularly well are the raised moraines on the Dugdale Glacier to the south of Robertson Bay, and those at Hell's Gate—the seaward end of the Priestley-Corner-Campbell Confluent-Ice. In both these cases, we have the rather unusual case of a medial moraine of sufficient density to act as a protection to the ice on which it lies, so that, owing to the greater ablation of the clear ice, the rock-covered ice stands from 20 to 50 feet above the general level of the glacier, thus having the appearance of giant ribs (Plate CXLIII, Chapter VII).

Small and local moraines of this type are not lacking in the Antarctic, but they are not of frequent occurrence, owing to the poverty of rock material in most medial moraines. It is on the lateral moraines of certain glaciers that this phenomenon reaches its greatest development. Probably nowhere in the Antarctic is this shown so well as on the Koettlitz western lateral moraine. Here, from Heald Island down to the Blue Glacier —a distance of about 25 miles—a moraine extends which to the casual glance, would appear to be formed entirely of rock *débris* (Plate CXCIII). In width this moraine varies up to two miles; and, though its general level is only about 100 feet above the glacier surface, the rock material extends a full 1000 feet up the slopes to the rock walls of the glacier valley. We have mentioned that, to the casual observer, the moraine appears to be composed entirely of rock *débris*, but a little industry with an ice axe at almost any place in the low-lying portion of the moraine is sufficient to lay bare a transparent air-free mass of ice at a depth of 3 feet or less below the surface. Indeed, at two widely separated places on the moraine, the ice was already exposed—in one case as a fairly steep slope facing the north-east; while, in the other case, it had been laid bare by the eroding action of a small stream opposite Heald Island. In the latter case, a vertical cliff of ice about 50 feet high was covered by only the thinnest veneer of loose morainic material (Plate CXCIV). Though we have no definite evidence bearing on the subject, it seems quite possible that the higher portion of these moraines, also, may be but a comparatively thin covering of rock over ancient glacier ice.

The "Stranded Moraines" at the terminal face of the junction of Blue Glacier and the Butter Point piedmont, are similar ice-borne moraines, and are probably a continuation of the Koettlitz lateral moraine which has just been described.

The remarkable physical feature known as "the Ramp," within a quarter of a mile of the main winter quarters at Cape Evans, is in all probability somewhat similar in

places, with the difference that here we are dealing with a terminal moraine of the Barne Glacier, instead of a lateral moraine. It is certain, in any case, that the Ramp rises to a greater height than the glacier alongside it, and that the moraine *débris* rests directly upon ice in several widely separated places.

The protective action is, however, by no means confined to moraine material. Wind-borne sand—or stream-borne sand, if in sufficient quantity—will cause exactly similar effects; and even the occurrence of large sheets of alga in the fresh-water lakes found on certain Antarctic glaciers, and on the tidal platform which fringes much of the Antarctic Coast may exercise the same protective action. There is, however, one difference. The effects of these latter causes, when observed in the Antarctic, have always been on a much smaller scale than those just described.

It is the combined result of these three agencies—rock, sand, and to some extent alga, which give rise to that particular curse of sledge parties, the "pinnacled-ice.,"* which is so well developed on the Koettlitz Glacier. The term pinnacled-ice is here used to include all the forms of ice which are due to the thaw and ablation caused by the occurrence of sporadic beds of dark material on the surface of a glacier, when this action is aided by the erosive effect of the running water produced by such a thaw. The well-known "penitent-ice" is perhaps the counterpart of this type in more genial climates. Plate CXCV shows an example of penitent-ice from the Ferrar Glacier.

In its most picturesque form, the pinnacled-ice is chiefly due to the action of a moderate amount of sand—a quantity sufficient to cause the maximum amount of thaw-water, but insufficient to exert any general protective action (Plates CXCVI and CXCVII).

The general course of affairs may be sketched somewhat as follows:—the dry sand ablated out of the ice by the wind in the colder months of the year is redistributed by the same agency, and collects largely in the hollows and depressions already existing, that is, in the major depressions already cut out by streams, or caused by similar natural agencies, and in the minor depressions which are the result of the sculpturing action of ablation, and which are in general a foot or so apart. The influence of the sun's radiation on the sand gathered in the ablation depressions causes the formation of cryoconite holes on the slopes of the ice. The latter, as already described, weather exceptionally quickly and in such a manner as to present to the sun declivities much steeper than those which existed previously. As the cryoconite holes on the slopes develop in depth and width, a period arrives when the ice-walls of the holes melt through, and allow the water to drain out and to carry with it a portion of the sand at the bottom of the holes. This it deposits on the more level ice surfaces below. Here, in the course of time, sufficient sand may be deposited to form a protective layer, and, in the summer, the terraces thus formed may become the higher portions of the ice. The close of the summer thaw season usually sees most of the sandy material again firmly cemented to the glacier surface. During the following winter, ablation works steadily; and, as the ice cement

* H. T. Ferrar, 'Geological Memoir of the "Discovery" Expedition, 1902–4.'

is removed from between the grains, more and more of this sand is loosened, and this loosened material is swept by succeeding gales into all depressions.

The action of the water is often only effective in carrying the sand to the level of the small local plateaux or terraces, but in certain places, as on the Koettlitz pinnacled-ice, the action of the thaw-streams is of greater importance. Indeed, in the height of summer here, the deep ravines separating the 50-foot pinnacle-ridges, are occupied by streams 3 or 4 feet deep and several yards wide; and these must carry quite a quantity of sand, a load which they will sooner or later deposit in the sea or on the sea ice at the entrance of the glacier valley. It is probable that the erosive action of the water in these streams is not inconsiderable.*

The characteristics of the pinnacled-ice studied by the present Expedition may be enumerated as follows:—Pinnacles with a maximum height of 50 feet, with stepped or vertical sides due to the formation of deep cryoconite holes on a steeply sloping surface; the formation of flat sand deposits sometimes several square yards in area on the steps and terraces; and, finally, the occurrence, in the hollows between the pinnacle ridges and below the steps, of fairly large streams carrying a great deal of silty material.

From a comparison of the amount of water flowing on the surface of Antarctic glaciers, during a period of maximum thaw, with that seen on the surface of glaciers in temperate regions, one might be led to the opinion that the amount of thaw here is quite comparable with that occurring in regions beyond the Polar Circles.

Such an opinion would, however, be quite erroneous, for the distinguishing characteristic of our thaw is that by far the greater portion of the water is supraglacial. It is true that examples are not entirely lacking of englacial streams, but these latter are quite the exception, and the stream channel in the Priestley-Campbell-Confluent-Ice is almost the only good example of the phenomenon that we have met.

This tendency of our streams to keep to the glacier surface has a physical explanation, and is due primarily to the low temperature within the body of the glacier, whereby water, even if able to penetrate by way of small crevasses, will become frozen before it can travel any great distance. Another contributing factor of almost equal importance is the low temperature of the water forming the surface streams.

That this tendency is a real one, is proved by the fact that, on the glacier surfaces in the southern portion of Victoria Land, the rivers and streams do not appear to erode their beds downwards to anything like the extent they do in temperate latitudes. It is, in fact, quite exceptional to find the beds of supraglacial streams or lakes countersunk to a depth of more than a couple of feet. One exception, however, is the case of a surface stream on the Koettlitz Glacier, which had cut a tunnel about 6 feet in diameter, and the bottom of whose channel was a full 9 feet below the glacier level. Plate CXCVIII shows a similar stream channel in Corner Glacier.

One other example of an ice canyon about 8 feet in depth was seen cutting through consolidated snow-drift which blocked the bed of a stream draining the Davis

* The water from these streams floods considerable areas of sea ice in the early summer, and much assists the dissolution of the latter.

Glacier. The conditions here were, however, unusual, since the stream before meeting the ice dam had flowed a full 2 miles along a sand-paved valley strongly warmed in the sun's rays. Perhaps the best example seen of a deep thaw channel is one on the Priestley Glacier, which is illustrated in Plate CLXXV.

On the Ferrar and Koettlitz Glaciers, however, streams may be followed for miles along the surface without disappearing into the glacier. This could hardly occur on glaciers which were heavily crevassed, and the mere mention of this fact gives a clear idea of the general freedom from crevasses displayed by these glaciers, at least in the depressions or lower portions of the glacier surface.* This freedom from crevasses may be attributed largely to the mature character of the valley bottom of these outlet glaciers. True moulins were not seen by us, with one or two insignificant exceptions, north of 75° south latitude ; though structures which simulated the appearance of moulins, but which could not have been produced by the agency of thaw-streams, were not uncommon.

Evidence of the low temperature of the body of the ice is also furnished by the occurrence of lakes on the surface of the glaciers (Plate CXCIX). The best examples were to be seen on the Koettlitz Glacier, and one of these cannot have been less than a couple of miles in diameter. It is seldom, indeed, that one meets surface lakes of any considerable dimensions on the better-known glaciers in temperate regions, and the reason for their occurrence on the larger and gently sloping glaciers of the Victoria Land region is probably to be found in the freedom of the ice from crevasses, combined with a low temperature within the body of the ice. Even in the Antarctic, it is only on the gentler slopes (where, in many cases, the glaciers are afloat) and on the flatter portions of masses of Piedmont-Ice that the lakes reach any considerable size.

The most common occurrence of lakes is naturally in the depressions of an ice surface which is copiously strewn with rock *débris*. Here, the action of the sun is intensified by the radiation from the rock, and the two influences are able to bring about melting of the drift snow, the water collecting in the depressions to form lakes. By far the greater number of these lakes are to be found on the uneven surface of the lateral ice-borne moraines. Good examples of such lakes are to be seen on the Koettlitz Glacier lateral moraine, on the Stranded Moraines in McMurdo Sound and on the lateral moraine of Corner Glacier. These are probably due to a peculiar configuration of the surface, slopes being in general fairly steep, and the depressions isolated from one another, so that the tendency is towards the formation of numerous lakes without outlet streams. The lakes are seldom more than 100 feet in diameter, and are generally several feet deep in the centre (Plate CC).

Lakes of this kind are found, not only in the lateral moraines, but at times also on the medial moraines of a glacier ; though here their size is strictly limited by the breadth of the moraine itself. When the medial moraine is of such density as to act as a

* This freedom from crevasses is due to an extremely small and uniform gradient, and occurs in spite of a greater tendency of the ice to crack in the low Antarctic temperatures. These factors work in opposite directions, and both need to be borne in mind, since both have great significance in the study of Antarctic ice-formations.

protection to the ice beneath, and the moraine is raised above the general level of the glacier surface, lakes are generally, as on the Priestley Glacier, formed beside and below the raised moraine. Such lakes are therefore in general considerably longer than they are broad. Examples have been observed with a width of only a few feet and a length of about 40 yards, while some reach a depth of at least 10 feet (Plate CCI).

It is also a common thing to find lakes of considerable size in the lateral radiation gullies of the glacier; and here, owing to the steep slopes of the banks on either side, the lakes have in all probability a considerable depth. A very good example of such a lake is seen on the south side of the Ferrar Glacier close to Cathedral Rocks, the lake having a length of half-a-mile and a width of over 100 yards.

We have next to consider what becomes of all the many streams which are visible on the glacier surface in the middle of summer. Here two different cases may be recognised: first, that of the streams on glaciers which terminate on land; and, secondly, those on glaciers whose end is washed by the sea.

In the latter case, the thaw-water generally flows directly into the sea or on to the sea ice through the medium of the surface streams already described, as is the case with the Ferrar Glacier. In the former case, which usually occurs only for small tributaries which have cut for themselves no very definite bed, the streams flow down from the snouts of the tributary glaciers, and go to swell the volume of the lateral streams at the sides of the main valley glacier.

One case where the main glacier does not reach the sea is, however, known. The Taylor Glacier, together with the Canada and Australia Glaciers, all end in a snow-free valley at some distance from the sea. Here a very peculiar state of affairs exists. All the thaw-water from the Taylor Glacier, together with the water of the small streams from a few tributary glaciers, flows into Lake Bonney. Thus, the water gathered from an area of about 100 square miles collects and forms a lake without an outlet, which was roughly estimated to contain, in February, 1911, 36,000,000 cubic feet of water.

Clearly the lake represents the accumulation of thaw-water from the Taylor and smaller glaciers for several years. Since evaporation exceeds precipitation in this area, and since the inequality will be least on the glacier surface, we are safe in stating that the total amount of thaw-water formed on the Taylor Glacier (say, 30 square miles in area), less evaporation from the water *en route* to and in Lake Bonney, cannot exceed 36,000,000 cubic feet,* or a loss of about 1/30 inch from the glacier surface in the form of thaw-water. Clearly, loss by evaporation is much greater than loss by thaw in this area.

One of the most curious results of the tendency exhibited by Antarctic glaciers to extend into the sea in the form of floating ice-tongues, is the formation of thaw-water lakes on the flat, free-floating portions of the glaciers. These are largely caused by the inability of the thaw-streams to flow directly into the sea, and this is due in its turn to

* This estimate is based upon the amount of *water* present in March, 1911, and is an extreme outside estimate. The correct figure is probably very much less.

the slightness of the grade of the upper surface on the floating portion of the glacier, and to the low temperature which limits the erosive power of the surface water. During the first western geological journey in February, 1911, the form of the surface of the Ferrar, and still more of the Koettlitz Glacier, led us to agree with the opinion already expressed by the geologists of the Shackleton Expedition*—that the lower floating portions of those glaciers are largely made up of frozen thaw-water which has come down from the upper levels of the glacier in the form of surface streams.

Mention might here also be made of the not infrequent occurrence of "slush" lakes on Antarctic glacier surfaces: these are formed by the flooding with thaw-water of hollows filled with drifted snow. They occur very commonly in the lee of the cliffs of glacier valleys, the best examples having been seen on the Ferrar Glacier.

For a full discussion of the formation of lakes in rock basins in the Antarctic, the reader is referred to the 'Shackleton Geological Memoir.' Within safe walking-distance of their hut at Cape Royds, the geologists of the Shackleton Expedition had a large number of these lakes with different saline-content, and were able thoroughly to investigate their structure and internal constitution. The chief interest in these lakes undoubtedly centres round the manner of their formation, and this question will be dealt with in another volume of the present series of memoirs.

Though the amount of melting on the glacier surface, due to the thawing action of surface streams and lakes, is undoubtedly small, the same can hardly be said of the melting action of sea water on the snouts of those glaciers which reach the sea.

The cause of this is twofold: first, the presence of salt in sea water induces melting of fresh-water ice at temperatures below the freezing-point of fresh water; and, second, the ocean currents tap reservoirs of heat which are not available to the thaw-water present on the glacier surface. It has, indeed, been estimated that water above freezing-point is some hundred times more effective as an eroding agent than air at the same temperature.

It is clear also, from the local character of many ocean currents, that the melting action of the sea may vary within very wide limits at places but slightly differing in position.

Summary of Results of Ablation and Thaw in Victoria Land.

To estimate the total thickness of ice which disappears from the surface of the Victoria Land glaciers in any particular year, is a matter of considerable difficulty; and, in the absence of accurate data, such an estimate can hardly be put in any form other than as an expression of opinion. The difficulty is further complicated by the fact that the amount of ablation is very largely governed by entirely local conditions, so that glaciers differing but slightly in latitude may be subject to quite different amounts

* David and Priestley, 'Heart of the Antarctic.'

of denudation. Thus, on the western half of the Koettlitz Glacier, we have seen that the amount of thaw and ablation is immensely greater than that on the eastern half, or on the Ferrar Glacier; and this must be due to the large amount of sand which is present in the former case.

An example of the other extreme is afforded by the season 1911–12 on the Beardmore Glacier, in latitude $83\frac{1}{2}°$ S. to $85\frac{1}{4}°$ S. Though the passage of the Southern Parties up this glacier took place in the very middle of summer, no running water whatever was seen; and the single example of still thaw-water noticed during that time was on Christmas Day, in lat. 84° S., when about a pint of water was found in a small depression in the upper surface of a large boulder.* It is certain that no signs of stream channels were seen either on the outward or homeward route, and it is therefore probable that practically the whole of the loss taking place from the surface of the Beardmore Glacier in a normal summer is in the form of vapour by processes of ablation.

In the absence of any data, no attempt can be made to estimate the actual amount of ablation from glaciers such as the Beardmore; but the lack of thaw-stream channels, the low mean temperatures, and the small altitude of the sun, all indicate that it is here considerably less than in the latitude of the Ferrar Glacier.

Even for the vicinity of winter quarters, the data are so meagre as to give results which can by no stretch of the imagination be considered accurate; but an estimate of the total annual loss from a clear ice surface, at sea level, as from 6 to 12 inches, is certainly not far from the true value, the figure being probably nearer 6 inches for Cape Evans and nearer 12 inches for Cape Adare.

Thus, the annual ablation in the Antarctic is very small compared with that observed in other parts of the world, even at considerably greater altitudes. This want of proportion is especially noticeable, if we compare our estimate for the Antarctic with the observations made by Drygalski in Greenland, where the total loss in the year is 2·25 metres at a height of 100 metres above sea level, a result nearly nine times as great as our maximum estimate for the loss at sea level. Table XI gives a comparison between the observed ablation in different parts of the world:—

TABLE XI.

Observations by Blumcke in Switzerland:—

Height in metres...	2325	2467	2582	2639	2725
Ablation in metres per year ...	7·62	5·65	3·87	2·95	2·38

* This was evidently due to the melting of a small amount of drift snow; and, though it was the only water seen, it is quite possible that a certain amount of still water, or even flowing water, may have been formed in the beds of the lateral gullies at the sides of the glacier.

Observations by Drygalski in 70° 30′ N. :—

Position.	Height in metres.	Ablation in metres per year.
Asakak Glacier	100	2·25
Semiarsut Glacier	570	2·00
Kome Glacier	500	2·22

Observations by Axel Hamburg in 67° 20′ N. :—

Height in metres...	970	1000	1100	1200
Ablation in metres per year	3·3	2·4	0·9	0·04

Though our estimate (in the mean about 9 inches of water per year at sea level) is small, it is large compared with the ablation which must take place on the Polar Plateau at altitudes approaching 11,000 feet, where thaw is entirely lacking, and where ablation must be much smaller if there is a similar tendency towards decrease of ablation with height in the Antarctic, as, according to the figures in Table XI, takes place in Greenland.

CHAPTER IX.

THE ANTARCTIC ICEFOOT.

General Description and Types.

Except in the late summer months—December, January and February—and, indeed, during a normal year, for the greater portion of these months also, the Antarctic Continent may correctly be said to be completely girdled with ice.

A considerable portion of this ice is Land-Ice; that is, it consists of the seaward faces of large or small glaciers.

This does not come within the scope of the present chapter; though, if the glacier is small and its end aground, it is often itself fringed with an "icefoot" of a particular type.

The Antarctic Icefoot, however, includes the whole of this girdle, with the important exception of that portion which is formed of the cliffs of glaciers. Its presence has a very practical aspect for the explorer, because most types of icefoot render landing from boats very difficult, except towards the latter end of the summer season. It may, therefore, under certain circumstances, greatly lengthen the disembarkation of shore parties and their stores.

No full consecutive account of the formation of the Antarctic Icefoot has yet been given, the nearest to a full description being that in the Memoir of the Shackleton Expedition, 1907–9. It is intended here to go into the matter fairly exhaustively, dividing the icefoot into definite classes, and describing the formation and disappearance of the Icefoot of 1911 at Cape Adare in some detail.

Three main types of icefoot may be recognised, and it seems possible that these types will be found to embrace all those formed in other parts of the world where the air and water temperatures are sufficiently low to produce an icefoot at all.

Each of these types may be well represented for short distances along a coast, but more usually—indeed, almost invariably, when any great length of the shoreline is considered—two or three of them are found in combination. Nevertheless, their mode of formation and their form differ to such an extent, and are so dependent on their environment, or on the weather which prevailed at the time of their formation, that the types can reasonably be dealt with separately, before considering them in their joint relation to the Icefoot of any particular region of the coast. The three main types are:—

(1) The tidal platform icefoot.
(2) The storm icefoot.
(3) The drift icefoot.

To these may be added the more uncommon, but certainly not negligible varieties :—

(4) The pressure icefoot.

(5) The stranded floe icefoot.

All or most of these types may be seen in any special " region " of the Antarctic which has a diversified climate and a varied coastline. As these two factors occurred in conjunction both at Cape Adare and at Cape Evans, all the icefoot types were to be studied at each place.

As the icefoot in Robertson Bay was watched under peculiarly favourable conditions throughout a whole season of icefoot life; and, as it was perhaps the finest example of its kind that has ever been observed, and it has not previously been described, it is proposed to give a detailed description of it in the latter portion of this chapter, and only to refer cursorily to the icefoot at the other bases of the Expedition.

Before entering into a discussion as to the formation, alteration and disappearance of any particular composite icefoot, the characteristics of the five ideal types will be described, together with the circumstances of weather and environment which are the chief factors that determine their particular form.

The " Tidal Platform " Icefoot.

This type is one of the most widespread of all forms of icefoot. It occurs either with or without the other types, and along almost the whole of the coastline which is not fringed with Land-Ice. Indeed, it is much more common than would appear at a first casual glance; for, actually, it is often masked in its earlier stages by the superposition of a " storm icefoot," and, in its later stages, by the piling up on its surface of a " drift icefoot." Together with stranded sea ice, it forms the foundation of most composite icefoots, and, in addition to this, it is the most striking feature along considerable stretches of coast.

It is formed during the colder months of the year by the rise and fall of the tides, and its thickness may, therefore, be pretty well gauged if one knows the difference between the height of sea level at low tides and at the highest spring tides which occur during the winter months. Though " frazil " crystals may be added to its under side during the winter, the actual thickness of the " tidal platform " will not be very much greater than the tidal range. This is true, except in special circumstances such as occur along a shallow coast, where it may be sensibly augmented by the formation of " anchor ice," or such as result in additions to the upper surface of the types that have already been mentioned. These additions may convert the original " tidal platform " into a composite icefoot either of the " storm " or " drift " type.

The " tidal platform," as typically developed, is formed by the deposition of ice directly from the sea water as it rises and falls with the tide, and laves the colder surface—first of the cliffs, beaches and glaciers of the coast, and afterwards of the seaward edge of the cincture of ice developed by this process. Its formation does not

commence until the temperature of the air and of the land have fallen considerably below the freezing-point of sea water, and until that of the sea water itself is also very near freezing-point. At first, the ice that is deposited during the night or during the cold "snaps" is removed during the day, or in warmer weather. For a considerable time, even when normal temperatures are uniformly low, the solvent and mechanical action of the waves which accompany a gale will remove the icefoot developed during the calm spell which immediately preceded the wind.

Finally, however, the steady deposition from the sea overcomes all obstacles, and, during the winter, the "tidal platform" in favourable districts increases in width very rapidly.

The shape and appearance of an ideal tidal icefoot, formed under favourable circumstances, is shown diagrammatically in the accompanying figure (Fig. 104), which is a slightly idealised section through a portion of the icefoot on the northern shore of the beach at Cape Adare.

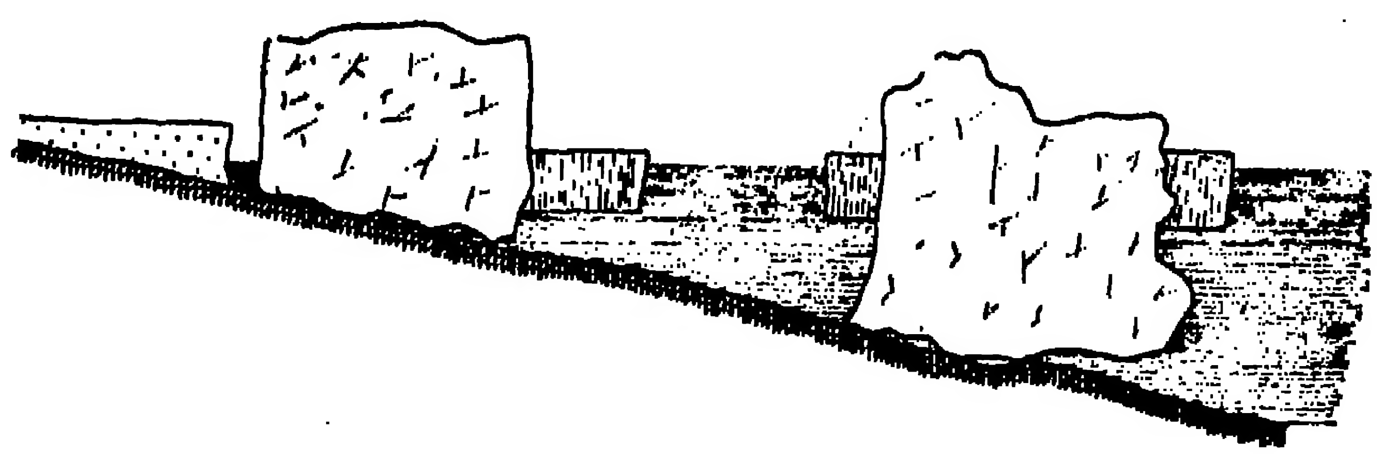


Fig. 104.—"Tidal platform" at Cape Adare.

The importance of this type of icefoot to the explorer, and especially to the geologist, is immense, and will become obvious as the other types are explained and described. Considerable stretches of the coast are only rendered accessible during the winter months by these tidal platforms, and they provide excellent camping grounds for sledge parties during coastal exploration (Plate CCII).

The Northern Party, during their work in Robertson Bay, again and again had cause to be grateful to the tidal icefoot. Much of the geological work would have been left undone had it not been for the flat shelf bordering the land.

The height of the tidal platform is dependent, as already mentioned, on the difference between the sea level at the maximum of the spring tides and that distance below sea level at low tide to which the effect of the cold air temperatures can penetrate; its growth in breadth is determined largely by the configuration of the part of the coast on which it is growing.

If the coastline is an open one, free from land-locked bays, so that the ice is not fast bound to the shore, the tidal platform may reach a breadth of many—in extreme cases, as much as a hundred—yards. If, on the other hand, the icefoot is formed in a deep or narrow inlet, it will seldom be more than a few yards broad, its breadth being limited by the amount which forms before the sea ice finally reaches such a thickness that it does not give way easily. The fresh deposits to the tidal platform will then be scraped off as fast as they are formed. In such a case, the attrition between the sea ice and the seaward edge of the icefoot is attested by the continual groaning and creaking, which is always to be heard in the neighbourhood of the working tide-crack which bounds the

Fast-Ice of the bay. Of course, if the autumn gales remove the sea ice, the ordinary course of the building of a tidal platform is resumed immediately the gale is over.

It will still not be a prominent feature, however, for the whole portion formed before the commencement of the gale is likely to be removed by the sea; or, if the temperature of the sea and land are too low to permit denudation taking place on a large scale, it will be masked by the deposition of a "spray" icefoot upon it.

It will be seen from the foregoing discussion that the most favourable circumstances for the formation of a broad icefoot of the tidal platform type, sensibly thicker than the extreme tidal range, will be on an open coast sloping gradually below sea level, and facing in such a direction that any spray formed during gales will be blown away from the shore. This situation occurs in the case of the icefoot on the northern shore of the Cape Adare beach, and in North Bay at Cape Evans (Fig. 105).

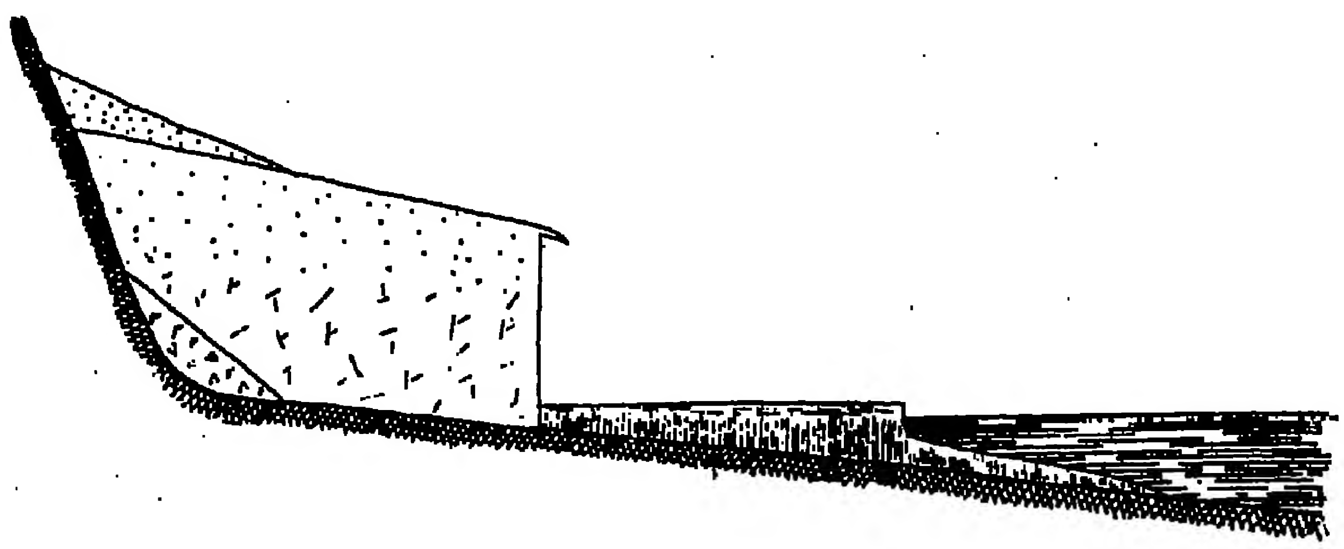


Fig. 105.—"Tidal platform" icefoot, north beach, Cape Adare.

The most favourable conditions for the formation of a broad tidal platform which shall be almost coincident in thickness with the height between tidemarks, is, on the other hand, along a similarly open coast which is formed by a rock bluff dipping at a steep angle below the sea, as at the bluff end of the peninsula of Cape Adare (Fig. 106).

Finally, the most favourable conditions for the formation of a well-marked tidal platform of the narrow bay type is along a land-locked coast in a region marked by

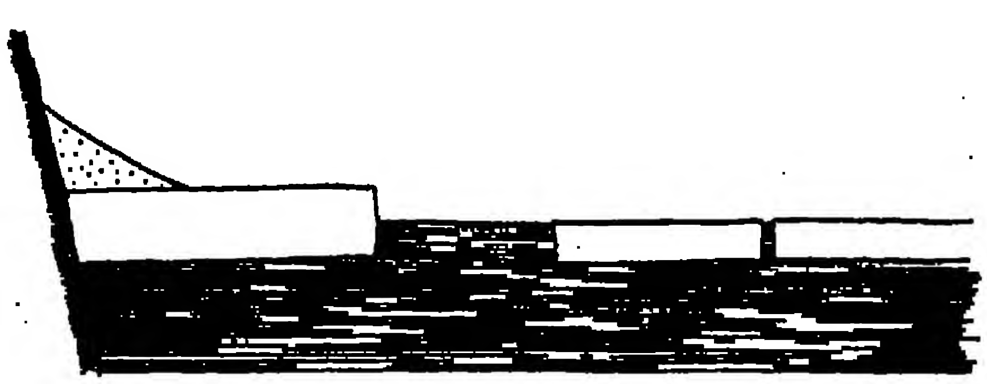


Fig. 106.—"Tidal platform" icefoot, north end of Cape Adare.

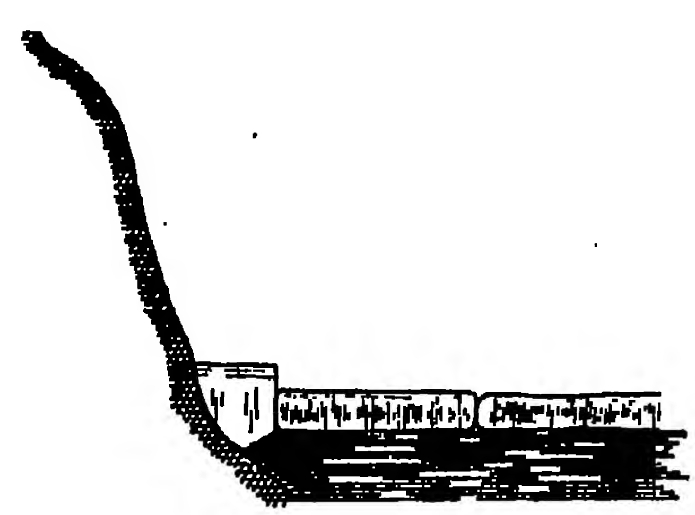


Fig. 107.—Narrow tidal platform, Robertson Bay.

very few violent storms with long continued periods of calm between them (Fig. 107). Here, the tidal platform will form in the autumn through the chilling action of the coasts on the sea water bordering them. This formation will commence slightly before the sea begins to freeze, the formation of sea ice being retarded by the circulation of the main currents and the constant interchange of warm and cold water through the regular ebb and flow of the tides.

When the sea ice does form, it will remain in the bays until its break-up in the next summer or early autumn, and by constant friction will keep the tidal platform within its original bounds.

A good example of such a narrow tidal icefoot was to be seen along the shores of the little indentations which make up the coastline of the western side of Robertson Bay. The occurrence of a gale is here the exception rather than the rule, Robertson Bay, west of Penelope Point, being essentially an area of calms.

The tidal platform will commence to grow immediately the autumn fall of temperature sets in, but its manner of growth differs decidedly during the different seasons of the year. In the earlier and, to some extent, in the later stages of its existence, deposition and denudation go on side by side, and it is a combination of these in varying proportions which gives the final shape to the product of their joint efforts.

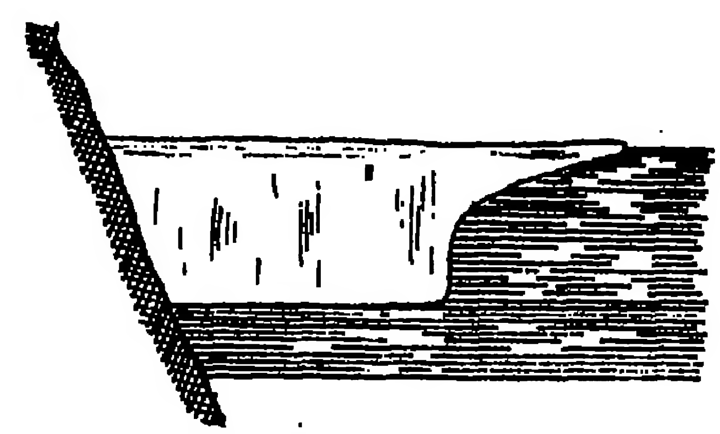


Fig. 108.—Platform with jutting edge.

Thus, in the early days of its formation, we see the platform everywhere growing more rapidly near its upper edge, and in special cases near its lower edge, than in its middle, and this gives it a section very much like Fig. 108 or Figs. 109 or 110.

The first of these cases is explained by the fact that the portion of the platform which is below sea level most of the time, is being denuded by the comparatively warm sea water almost as rapidly as it is formed. It is only along the upper portion, which is never covered by anything but a shallow film of surface water, and is therefore only exposed to the influence of water cooled by direct contact with the air, that growth is rapid. Growth becomes progressively slower towards the bottom of the outer face of the platform, and a jutting top therefore projects beyond a concave, sloping face (Plate CCIII).

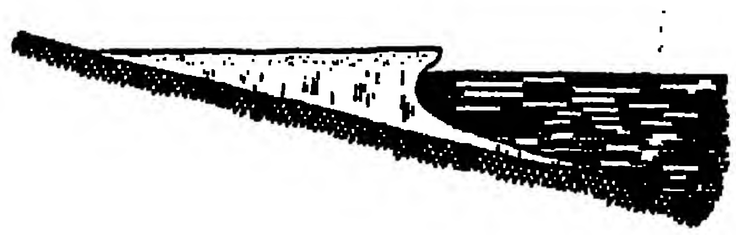


Fig. 109.—Tidal platform increased by addition of anchor ice.

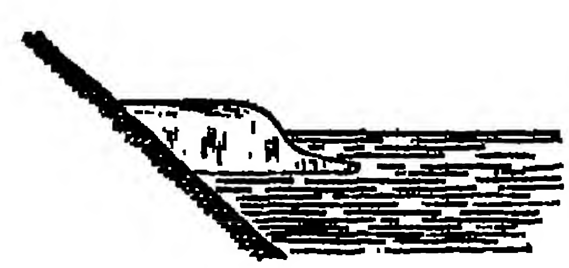


Fig. 110.—Tidal platform with a prow.

This action is obscured along shallow coasts by the formation of anchor ice, owing to the " supercooling " of the sea water. In these cases, the deposit of anchor ice may grow until it may almost be considered part of the tidal platform, to which the greater portion of it is added in course of time. This deposit of anchor ice often becomes continuous with the lower edge of the platform, and may extend several yards out into the sea (Fig. 105).

This mode of growth continues so long as the temperature of the sea water is potentially below freezing-point, and the icefoot grows quicker in its lower portions. If the sea at this time is free from ice, as may well be the case in regions swept

periodically by the Antarctic storms, the process continues until the form of the icefoot is reversed and a projecting prow is formed under water. The icefoot profile is then as shown in Fig. 110.

The ideal section is, however, complicated in nature by the action of a breaking sea on the windward side of capes and smaller projections of the coastline, and of the swell to leeward of the same features.

If, however, calm weather ensues and the sea ice forms, the projecting prow is never very much in evidence. As fast as it is formed, it is broken off by the abrasion at the tide-crack, and the type of platform edge which is usually seen in the winter months is the straight wall which is shown in Fig. 107. This straight wall is also well seen in Plate CCIV, which shows the bluff cliff of Cape Adare as it appeared in early September of 1911, when the old sea ice with its ridges and belts of pressure had been driven out by the hurricane of August 16, and the new ice formed since then was still unaffected by pressure. A very comprehensive view of a winter tidal platform is thus obtained. It is especially interesting, because, being in the lee of a high cliff, the icefoot is very nearly free from complications due to the addition either of sea spray or snow-drift, the only irregularities of any magnitude being due to the presence of one or two stranded floes thinly covered with spray, and some very insignificant drifts of loose snow. This is eminently a case where the real Antarctic icefoot approaches very closely to one of the ideal types.

The growth of these seasonal varieties of tidal platform is often complicated by slight roughness of the sea, which is not sufficient to cause spray and thus to render possible the formation of a "storm icefoot," and yet is enough to complicate the ideal forms described above. The usual effect of such a modification is to cause a sloping upper surface to the platform, which is the direct result of the continual washing of the water over the air-cooled surface of the ice above normal highwater mark (Plate CCV). Each type has, therefore, its corresponding "rough water" modification. In all three cases, as already mentioned, the formation of anchor ice may noticeably affect the shape of the ice sheet on a very gently sloping shore. The addition of drift snow to the upper surface of the platform has also been known to affect both its rate of growth and slope. No cases of this were seen either at Cape Adare or at Evans Coves during the present Expedition, but at Cape Evans this type of deposition was common.

Once the regular vertical growth sets in, little change which is visible to the naked eye takes place in the ice foot, except at occasional unusually high tides, when the sea water overflows a surface which is constantly being lowered by ablation and drift-chiselling. A fresh layer of ice an inch or two thick is then deposited as a white greasy-looking coating, easily distinguishable from the ice of the lower portion of the platform by the fact that it contains a much greater proportion of brine between the ice crystals. It is therefore more clouded and more liable to become damp with rise of temperature.

This difference in salinity was tested in a very practical and decisive manner by the Northern Party during their winter at Inexpressible Island, when they found that the

only ice which served to salt their stews sufficiently was that taken from such overflow deposits soon after they were formed.

A very pretty example of the effect of the combined processes of denudation and deposition which give rise to a horizontal lamination of the upper portion of the icefoot was also well seen at the same place, and is illustrated in Fig. 111. Two or three seals had been butchered in a hurry in March, had been dragged a few yards from the seaward edge of the icefoot and had then been left. Both the blood and the warm carcases of the seals sank into the ice a little before they froze. The former disappeared below the general level of the icefoot surface for a vertical distance of some 2 inches, and the latter were countersunk for about $4\frac{1}{2}$ inches (Fig. 111, A). As the winter went on, the plateau gale blew unceasingly, and ablation lowered the ice surface unusually quickly, until, by June, both the ice underneath the seal (protected from removal by the carcase), and the ice with which the seal's blood was mixed, stood out above the general level some 1 or 2 inches (Fig. 111, B). Soon after this, a series of unusually high tides overflowed the reduced icefoot, and some 5 or 6 inches were added to its height during the few days that these tides lasted. The seals and some sledging gear were frozen in so firmly that quarrying them out gave a good deal of trouble and occupied much time (Fig. 111, C).

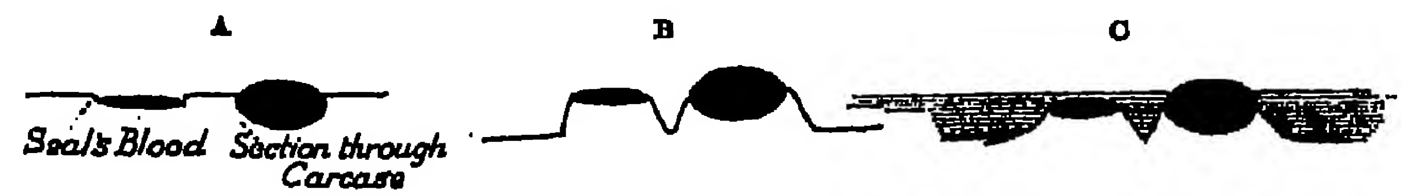


Fig. 111.—Seal carcase and blood on "tidal platform" icefoot at Inexpressible Island, winter, 1912.

Thus, it will be seen that the two main changes in the tidal platform during the winter are a steady growth seaward, and an occasional accession in height due to abnormal tides, the latter giving a horizontal lamination to its upper portion. The former growth may, however, be almost, or entirely, neutralised by the constant scraping of the sea ice along the seaward face of the platform.

The next stage in the life-history of the tidal platform commences with the general rise of air, earth and water temperatures which marks the passing of the spring.

As the summer approaches, the sea water commences to sap the icefoot from beneath, and the sun plays havoc with the surface, the latter agency being aided by the grit which has been blown on the icefoot from time to time during the winter.

The thaw-water which is formed drains away through the porous ice, and materially alters the structure of the lower layers, which have as yet escaped the direct influence of the sun. The icefoot thus becomes honeycombed through the agency of the products of its own dissolution (Plate CCVI).

In addition, the drainage from the land behind it has to pass through, over, or underneath it, and it may become dissected everywhere with stream channels. Thus its disintegration proceeds apace, while fresh impetus is given to its removal after the sea ice has broken up and has left the icefoot to the mercy of the swell.

The sea then commences to exert a mechanical effect as well as a solvent action. Huge floes, sweeping past under the influence of current and wind, may grind large pieces from the weakened structure; the waves, swelling upwards under the undercut

tidal platform, break off the projecting portions and use them as gigantic hammers with which to pound off more ; and the daily shrinkage increases many-fold.

As the weeks pass, the icefoot dwindles steadily until, usually, the tidal platform of the last year becomes a thing of the past (Plate CCVII). All is then ready for the formation of the next one, which will begin as soon as winter once more commences to grip the land.

The life-history of the first of our icefoot types has thus been passed in review. It is the type which is the basis of most composite types, and which is also frequently found flourishing by itself where the environment is favourable. The remaining four types all contain much ice which is the result of the processes outlined above, but, in each case, the greater proportion of the ice and the dominant characteristics of the icefoot have resulted from some special features of their surroundings and of the weather conditions under which they have been formed. They, therefore, belong essentially to classes of their own.

The "Storm" Icefoot.

This type of icefoot, as is suggested by the name, is only formed during winds, or while a heavy swell is breaking on an exposed coast. In the early autumn, when the temperatures—although quickly undergoing readjustment to winter conditions—are still fairly high, the effect of a heavy sea may be to remove the incipient icefoot which has formed, either as the beginnings of a tidal platform, or as a series of floes stranded and frozen together during a previous spell of calmer weather. Thus, at this period, the sea exercises predominantly a denuding action ; indeed, it is during the early autumn gales that the last stubborn remains of the previous year's icefoot are abraded or dissolved away.

As the winter approaches, a portion of the spray which is whipped from the top of the white-capped waves by the wind, is deposited on the shore and on the new icefoot as spray ice—a cloudy, greasy-looking type of ice which is characterised by innumerable little veins of brine and air, running in a fine irregular network over its surface and throughout its bulk. The blizzards have now become agents of deposition more than of denudation. Though the icefoot is still sapped from seaward, and projecting portions are broken off it by the impact of the waves, it rapidly increases in height by the deposition of spray ridges, while, if the gale is a really severe one, the loss in width due to the removal of its seaward edge is more than compensated by the increase in height on its landward side. The spray ridges may extend inland for a distance of 30 or 40 yards or more. They are arranged as long, approximately parallel ridges which vary considerably in height, but which all dip at a fairly steep angle towards the direction of the prevalent wind (Plates III and IV, and Fig. 112, and Plate CCVIII).

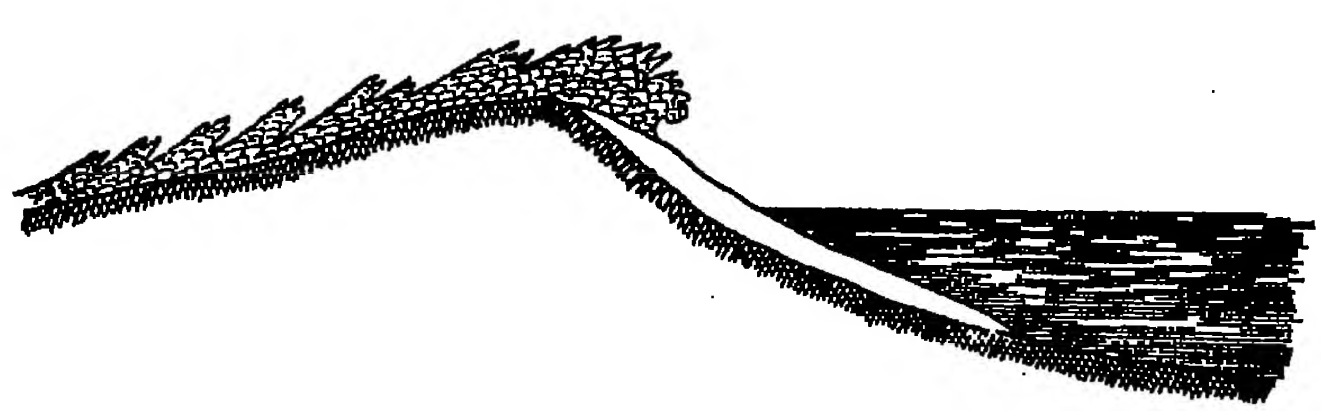


Fig. 112.—Spray ice on a 'storm' icefoot at Cape Adare.

In extreme cases, these spray ridges may be 1 foot or more thick and between 2 or 3 feet deep, and, after exceptional gales, the noticeable effect of the spray may extend inland for hundreds of yards. It is seldom, however, that it forms a permanent portion of the icefoot further back than 40 yards. Beyond that it is deposited as discontinuous flecks of ice, which are usually arranged on the *windward* side of any prominences (Fig. 113).

Fig. 113.—Spray ice deposited on the windward side of stones.

These are quickly removed by ablation, an efflorescence of salt only being left to mark their former position.

Such an extreme case of deposition was well seen by the Shackleton Expedition, 1907–9, and is described in the Geological Memoir. During the great autumn blizzard of February 18–21, 1908, when an extraordinarily low temperature (for such a gale) was registered, some 30 or 40 tons of stores, which had been landed between Flagstaff Point and Derrick Point at Cape Royds, were covered by such a spray deposit which reached in places a depth of over 6 feet. A year later, in spite of the intervening ablation and thaw, a trench had to be dug to a depth of 4 feet in order to salve four volumes of the "Challenger" Scientific Reports which had disappeared in the general *débâcle*.

An interesting corollary to this was recorded in 1911 by the Northern Party of the present Expedition. The site of the former trench dug two years before was not then visible, but just about where it must have been sunk was found a case of Lyle's golden syrup and another of bottled beer, both of which had been the subject of anxious search two years before, and both of which were now standing well above the surface of the ice (Fig. 114).

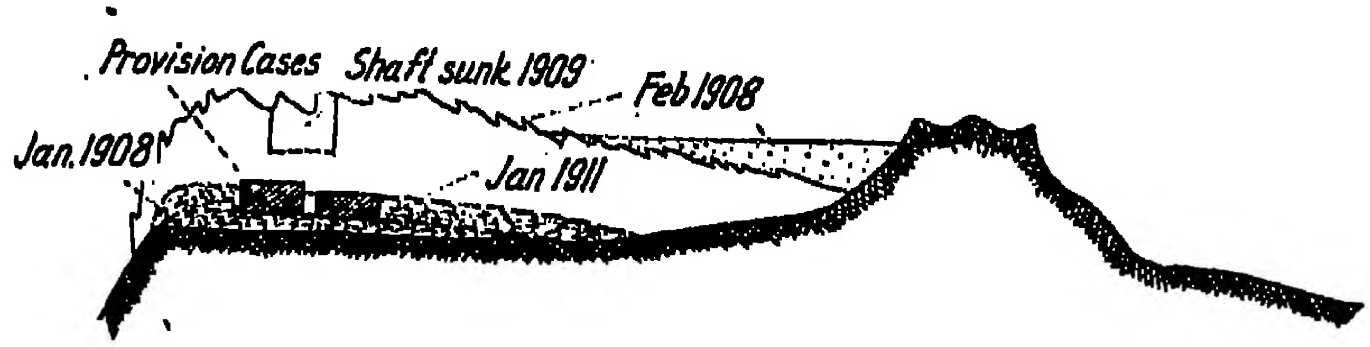


Fig. 114.—Storm icefoot at Cape Royds, as it appeared in January, 1911.

This result demanded either an unusual thaw during the summer of 1911, or the icefoot formed in February, 1908, must have been an exceptional one even for a storm icefoot.

Although the thaw in 1911 was possibly an abnormal one, it seems probable that the main reason for the removal of the spray ice is, that there had been no significant deposit since the one in 1908. Indeed, it is unlikely that the conditions for a sea as great as the one experienced by the Shackleton Expedition are common in February. There is usually more sea ice about at that time.

Such a spray icefoot must occur, in a greater or less degree, over a great portion of the Antarctic coasts—everywhere, in fact, except in the very few places where the weather is habitually calm.

We should, however, expect to find it developed in its greatest perfection on the windward sides of projecting points. That this is the case, will be seen from the detailed description of the icefoot at Cape Adare which follows these introductory paragraphs.

The chief characteristics of the storm icefoot are great height and overhanging projections on the seaward side, and steeply dipping spray ridges on the landward side. Pools of brine are often held between the high buttresses along the seaward edge of the icefoot and the rock cliff or upward-sloping shore behind them, and the storm icefoot is marked all over with an irregular coarse crenulation which renders it unmistakeable. Such an icefoot is often strewed with deposits of seaweed and shell fragments, many pieces of which become frozen in, and are then buried under fresh accumulations of ice. It is also not an uncommon thing to find beds of pebbles a foot or more thick intercalated in the flatter portions of a storm icefoot with such regularity that, when the formation is dissected in the following summer, the number and force of the greater gales of the previous winter can be judged with approximate accuracy from the section thus revealed.

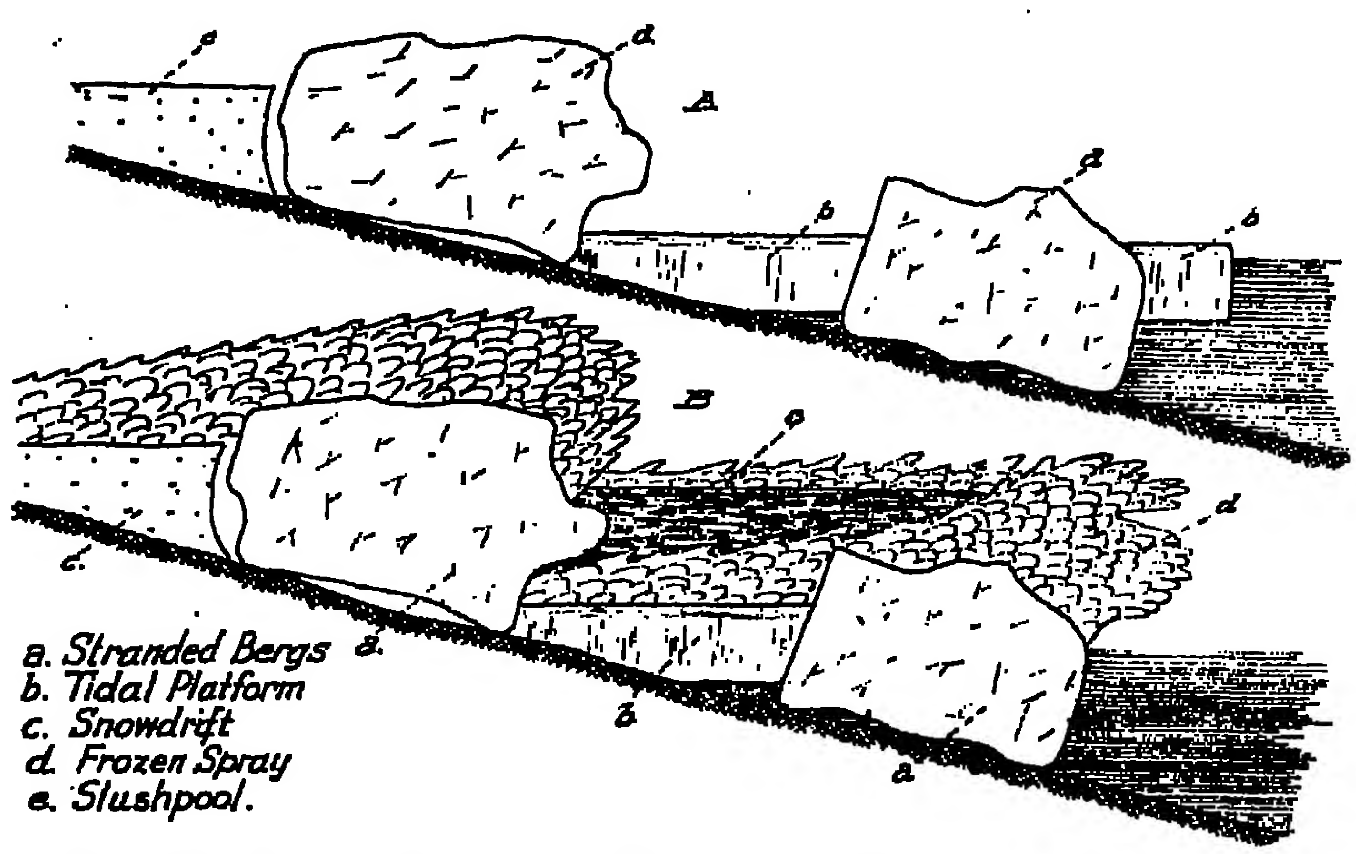


Fig. 115.—Comparative sections of the storm icefoot at Cape Adare before and after the May gale.

A storm icefoot certainly cannot be described as ephemeral, for, once formed, it lasts throughout the winter months. Such an icefoot is liable, however, to grow up during a single night; while twenty-four hours of hurricane with an open sea may completely change the appearance of those portions of the icefoot which lie in the path of the wind (Fig. 115 A and B.)

Plates CCVIII and CCIX illustrate portions of a typical storm icefoot formed after the ten days' gale at Cape Adare, in May, 1911.

Such a storm icefoot differs from the tidal platform type, in that it is difficult to scale, and so may render a good deal of the Antarctic coast impassable either for sledges or for men.

The "Drift" Icefoot.

This is perhaps the most noticeable type of icefoot along a coast of moderate steepness with a reasonable amount of snowfall or snow-drift. An icefoot of this kind may be divided naturally into two distinct parts, one of which is annual and the other perennial.

The annual portion will always be present in a "snow drift" icefoot: the perennial may or may not be, according to the configuration of the coast. It is this latter portion of a drift icefoot that forms quite a conspicuous feature of Antarctic coastal scenery, as seen from a ship in that portion of the year when the sea is free from ice. Wherever

steep cliffs or moderately steep slopes face the sea, one may observe long lines of stratified "ice-fans," which are formed by the coalescence of the lower portions of fan-shaped masses of Snowdrift-Ice. These are in reality nothing more nor less than screes formed of snow and rock *débris*. Their permanence is due to the nature of the materials which form them, and especially to the action which the rock has upon snow under the compacting influence of the summer sun, which brings about an exceedingly quick change from snow to ice in such rock-strewn cones.

It is the position of these masses of Snowdrift-Ice, and not their structure, which causes those which fringe the seashore to be of interest in the present connection. It may be repeated, however, that serious objections can be opposed to the use of the term "icefoot glaciers" as applied to what appear, from the description given, to be similar structures in other portions of the Antarctic. Exactly comparable ice-formations occur in positions which are in no way connected with the Antarctic icefoot, and this title would be distinctly a misnomer if applied also to them. Unless one general term is conferred upon all these "ice-fans," the type name will not have a genetic origin. It is because of this that all such structures are classed together in this memoir as "Snowdrift-Ice."

The annual portion of a drift icefoot will be a feature of almost any portion of the coast during certain seasons of the year. It is, however, distinctly less persistent than the other main types of icefoot already defined, for it is the last to be formed and the first to disappear. It is seldom seen in any great development until the sea ice has frozen, for, until then, the snow-drifts along the shore must be insignificant in size and extent.

As this icefoot was typically developed in the neighbourhood of Cape Royds, and as a full description is given in the Geological Memoir of the Shackleton Expedition, it will not, therefore, be described in detail in this chapter. A short recapitulation of its life-history and its mode of origin will, however, be given for the benefit of any readers to whom the Shackleton Memoir may not be accessible.

When the Fast-Ice has existed for some days, it becomes strong enough to resist the force of the gales; and, as soon as it has reached this stage, the drift snow, which is only carried in large quantities by the stronger winds, begins to settle upon it in large quantities.

This accumulation is of course greatest along that portion of the shoreline where a lee is formed by the wall of a storm icefoot along a steep rock shore, which may or may not possess a lining of Snowdrift-Ice; or, again, in lee of the cliff of a glacier.

In the lee* of these obstacles, snow-drifts accumulate, and, in the course of two or three months, may reach the surface of the icefoot or glacier. They may even, in particular circumstances, overtop this, thus adding appreciably both to the height and extent of the icefoot and to the accessibility of the coast (Fig. 116).

The drift icefoot may generally be expected to have reached its greatest size rather before midwinter. By this time, as much snow has usually accumulated as the low

* Similar, but smaller, drifts will also collect on the windward side of those steeper cliffs which face the wind.

sheltering cliffs will protect; and, after this stage is reached, denudation keeps pace with accumulation. When the snow-drifts have formed to a considerable thickness, the tide-crack or cracks are continued up through from the sea ice to the surface of the snow-drift, and the superincumbent mass of the drift depresses the shoreward edge of the sea ice below the level of the sea, causing at the same time a considerable rise of sea-water along the cracks.

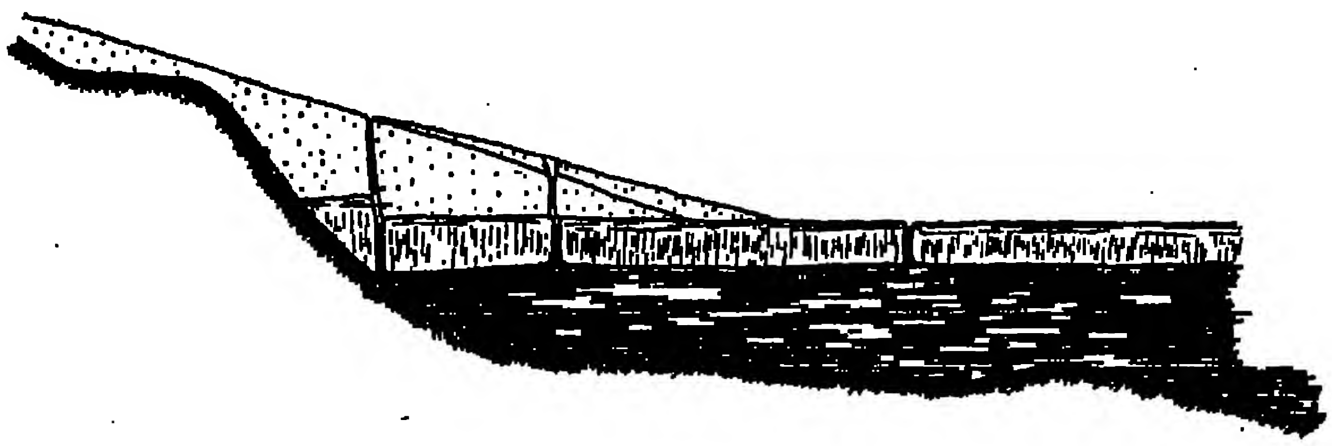


Fig. 116.—Section through a typical drift icefoot.

This sea-water percolates gradually into the drift on either side of the cracks, and adds very much to the compactness of the icefoot, turning the snow into an ice in which, however, the original granular structure of the snow-drift can distinctly be traced. The infiltration of this sea water, and its subsequent compacting action, adds decisively to the resisting power of the icefoot to the denuding agencies which act upon it during the later stages of its demolition.

With the exception of this strengthening process, little change takes place in the drift icefoot from now until the commencement of summer: denudation marches side by side with accumulation; accumulation with denudation. The angular forms of sastrugi of erosion occur together, side by side, with the rounded forms of sastrugi of deposition.

A slight softening and rotting of the surface of the drifts may take place with the approach of high temperatures and, locally, through the influence of included rock dust, this thawing effect may reach considerable proportions, a most pronounced honeycombing taking place which renders the icefoot extremely treacherous.

The next event of any magnitude in the life of the drift icefoot takes place when the sea ice breaks up and goes out, carrying with it all of the drift which extends beyond the working tide-crack.

After this, the warm sea water undermines the icefoot rapidly, and the disintegration of the annual portion is almost completely accomplished during the next few storms, the snow breaking off in huge cubical blocks to be carried away by wind and current, leaving the shore bare.

The solitary exception to this rapid disappearance of a drift icefoot is to be seen where the drifts run inland on a shelving rock shore, where the lee is provided by a cliff standing many yards back from the sea. In this case, the dwindling of the shoreward portion of the drifts is a much slower process, being confined to the influence of direct thaw, of radiation from the surrounding rock faces, of evaporation, and of drift-chiselling.

These agencies, however, continue the work slowly but surely, until the colder weather again sets in. They ultimately leave a nucleus of a stunted, discoloured

snow-drift with rounded contours, whose size is dependent on the clemency or otherwise of the season. This forms the basis of the next year's icefoot.

Two other varieties of icefoot are sufficiently distinctive to deserve mention, although neither of them is widespread enough in occurrence to warrant the creation of a special type to include it.

The "Pressure" Icefoot.

The first of these—the "pressure" icefoot—occurs sometimes in deep bays, or on portions of the coast which are exposed annually to severe pressure from the pack. Under normal circumstances, this pressure expends itself in the formation of ridges, which may parallel the shore, and are usually separated from it by a strip of bowed sea ice several yards, at least, in width.

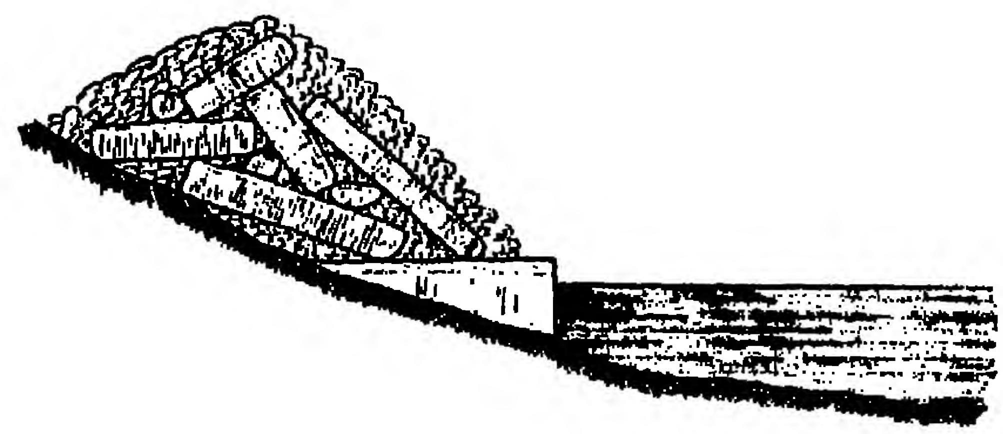


Fig. 117.—Pressure icefoot.

In favourable situations, however, such as in the two examples mentioned above, the inner line of pressure blocks may be crowded right up on to the shore or on to the tidal platform of the icefoot, even occasionally on to a high storm icefoot. If, under such circumstances, the sea ice is then removed by a gale, this pressure ice may be firmly bound together, and may be permanently incorporated in the icefoot by a cement of frozen spray (Fig. 117). In this way, an icefoot has sometimes been seen to increase in height by some 7 to 8 feet in a single gale.

The "Stranded Floe" Icefoot.

Finally, there is another variety of icefoot which is confined to coasts with a shallow foreshore, and this type may also be of local importance. Such an icefoot is formed initially by the stranding of floes and small bergs along the shore, and it was an icefoot of this type which formed the backbone on which the whole of the composite icefoot at Cape Adare was built up. Views of portions of such an icefoot in the making are shown in Plates CCX and CCXI.

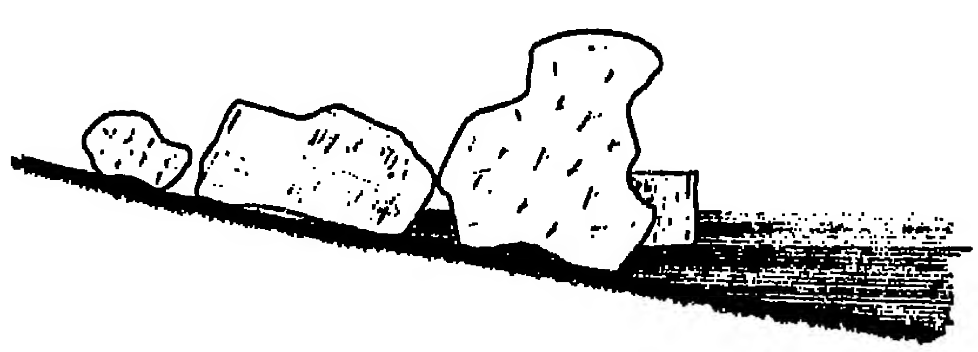


Fig. 118.—Stranded floe icefoot.

A section through this type of icefoot is shown diagrammatically in Fig. 118.

Before proceeding to a detailed review of the life-history of a composite icefoot, another mode of accretion which affects all types of icefoot alike, and which is sometimes the cause of appreciable additions, should be referred to: this is the deposition of water vapour in one form or another from the air.

During a considerable proportion of days in the life of an icefoot, air close to

saturation point is constantly being brought into contact with the cold ice, and this deposits a portion of its moisture.

The moisture deposited may take various forms, and these have been considered in Chapters I and II. It would be out of place to enter into a discussion of them here, because their characteristics are not dependent upon the fact that they have been deposited on the icefoot, but are rather a function of the atmospheric conditions under which deposition took place.

It must be remembered, however, that such vapour is a factor to be reckoned with in connection with the growth of the icefoot, just as lack of water vapour in the air bears a very distinct relation to its decay. Nowhere is this more the case than in those regions such as Cape Adare and Inexpressible Island, where open water may be seen, or its presence inferred, at any period of the year.

Disappearance of an Icefoot.

A few general remarks must also be made on the subject of the mode of disappearance of the icefoot. The type to which an icefoot belongs does not materially affect its disappearance, which is brought about in the main by the general rise of air and sea temperature which marks the approach of the Antarctic summer. A description of this process has already been given when dealing with the icefoot of the tidal platform type, and it holds good for other types also, with the difference that the disappearance of the storm icefoot is much accelerated by the large quantity of salt which it contains.

The commencement of the dissolution of an icefoot dates much farther back than this, however. From the very beginning of its existence, the powers of the different agents of denudation and deposition wage constant war, victory inclining now one way, now another. Throughout late autumn, winter, and early spring, the forces of accumulation triumph in general, though local victories on either side give an ever-changing outline to the disputed field.

On the one side of the conflict are ranged the spray—sometimes the unbroken waves—the snow-drift, and occasional deposits of pebbles and grit; on the other hand stands the wind, with its constant wearing action exercised through ablation and drift-chiselling, while the sea also denudes mechanically during gales when the sea is free from sea ice.

Until the sea ice forms, the forces first mentioned are overwhelmingly superior in their effects, but, from the time of the final freezing of the sea, the dwindling of the icefoot commences. The effects of the denuding agents are soon seen in the blackening of certain portions of the icefoot through the concentration of the grit which was held in the outer layers of ice; in the exposure of fresh patches of rock and gravel where the bosses of sea spray have been entirely removed; and in the bringing to light of large fronds of seaweed and of carcases of penguins which had been carried to the icefoot by the autumn winds, buried under accumulations of snow and spray, and are now finally once more revealed. The icefoot thus loses ground from the commencement of the

winter, and the loss is only partially repaired by addition through direct precipitation from the air. This loss, however, significant as it is, is very small when compared with the rapid destruction which takes place when the thaw sets in in earnest. From that date, the degradation of the icefoot proceeds with speed, so much so that it can no longer be traversed in comfort without the aid of thigh sea-boots.*

"Tidal Platforms" round Bergs.

Stranded bergs which cannot rise and fall freely with the tides, are often surrounded by a well-marked tidal platform. This is of importance, because its presence is a direct proof that the berg is really stranded, while the presence of large numbers of stranded bergs is in its turn a proof of the shallowness of the water in which they lie.

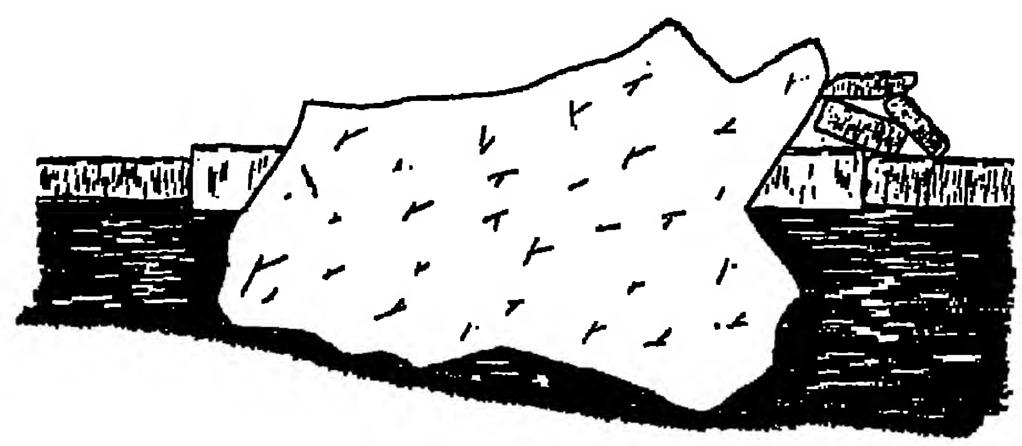


Fig. 119.—Section through a tidal platform round a stranded berg at Cape Adare in 1911.

Whenever such a platform occurs round a berg, it is proof positive that the depth of water is not more than four to six times the height of the berg above sea level, though it may of course be considerably less. Indeed, on coasts where such bergs are common, an approximate chart of the sea bottom might well be made with the help of such evidence as this.

A good example of such an icefoot round a berg is seen in Plate CCXII, and a diagrammatic section through a similar one in Fig. 119.

The Ridley Beach Icefoot.

The study of the Antarctic icefoot is best concluded by a detailed discussion of the formation, modification and destruction of a composite icefoot, dealing first with that along the beach at Cape Adare, a formation which was closely studied during the autumn, spring, and winter of 1911.

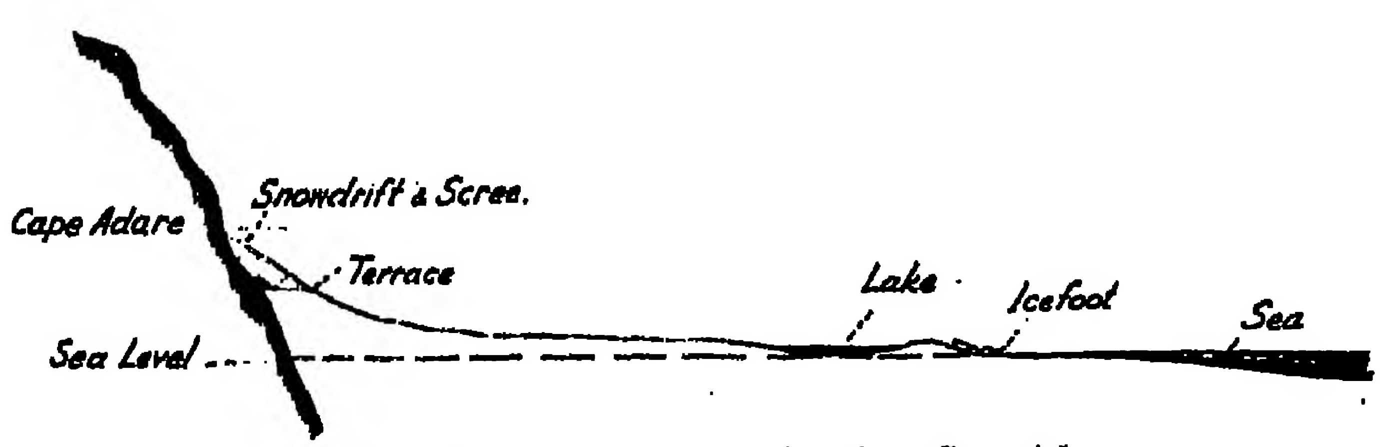


Fig. 120.—Section through the beach at Cape Adare.

The winter station at Cape Adare was built upon a triangular foreland of basalt pebbles, which had been deposited in the lee of the cape by an eddy of the tidal current which sweeps round it into the Ross Sea. This foreland is washed by the sea throughout the whole extent of two of its sides and the accompanying section (Fig. 120) gives a good idea of the low angle at which the seaward edge of the beach is inclined to sea level.

* This refers particularly to the icefoot in more northern latitudes.

The one side of the beach faces the north, and is thus exposed to the heavy swell which sometimes outruns the westerly gales and beats heavily along this portion of the Antarctic coastline, while the other side faces south-west, and is swept by the seas raised by the south-easterly gales, which are such a characteristic feature of the weather on the east coast of Robertson Bay.

According to the conditions which influence the mode of its formation, the Ridley Beach icefoot may thus be divided into a " northern " icefoot and a " southern " icefoot. The southern icefoot may again be divided, according to the base against which it is formed, into a " cliff " and a " beach " icefoot, the former being built up along the steep screes to the south and the latter along the beach itself.

The " Southern " Beach Icefoot.

When the " Terra Nova " arrived at the beach on February 18, 1911, and commenced the work of landing the Northern Party's stores, a few patches of discoloured ice which included beds of gravel were all that was visible of the last year's icefoot. It looked as if the thaw and seas had nearly accomplished their possible maximum of denudation, and the stores were therefore landed on what appeared to be permanent beds of gravel.

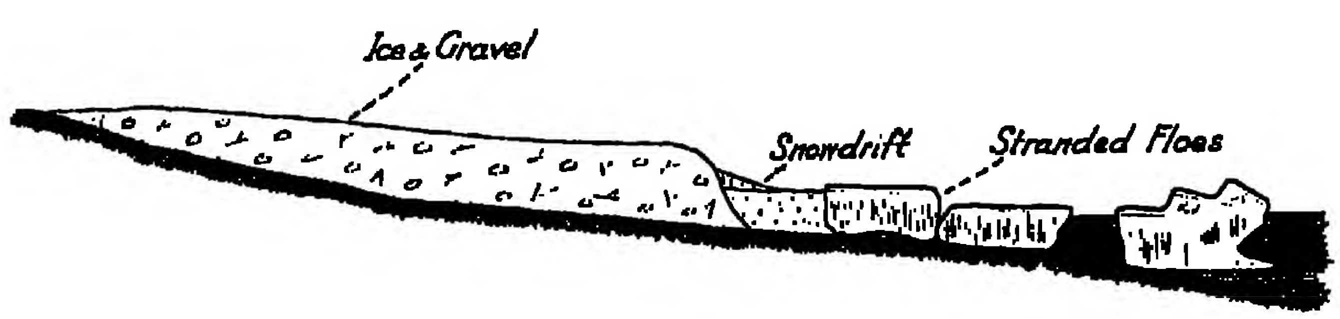


Fig. 121.—Southern icefoot, February 18, 1911.

The next few days, however, were marked by the beating of a steady swell against the icefoot of the southern edge of the foreland; and these beds of gravel, which proved in many cases to be resting upon the ice of the previous year's icefoot (Plate CCXIII), were gradually undermined and removed, with the consequence that a not inconsiderable amount of stores was lost, while many hours were wasted in removing those that remained to a safer position.

In the north, between the date of our landing and the commencement of the formation of the new icefoot, the sea had encroached as much as 12 yards on what we had thought was a permanent shore at the time of our arrival.

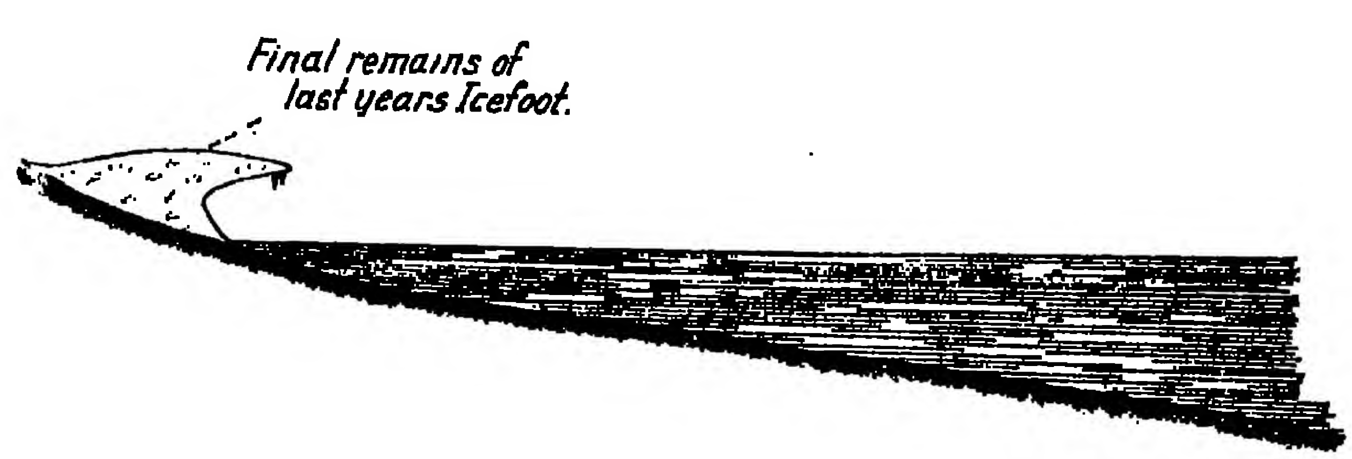


Fig. 122.—Southern icefoot, March 16, 1911.

The banks of gravel had evidently been formed by the concentration, by the action of the summer thaw, of the pebbles thrown up upon the previous year's storm icefoot. Fig. 121 shows the southern icefoot diagrammatically, as it was at the time of our arrival, while Fig. 122 illustrates the appearance of the same icefoot on March 16, 1911.

Towards the middle of March, the sea and air temperatures began to fall, foreshadowing the approach of winter; and, during the calm days of this period, deposition began to be significant for the first time, though the beginnings of the new icefoot were at first removed as soon as they were formed by the swell during the occasional spells of rough weather. This first icefoot was mainly formed of small pieces of very weathered pack and brash ice stranded on the shore by the action of the tides, and then cemented together by the freezing of the sea water between them (Fig. 123).

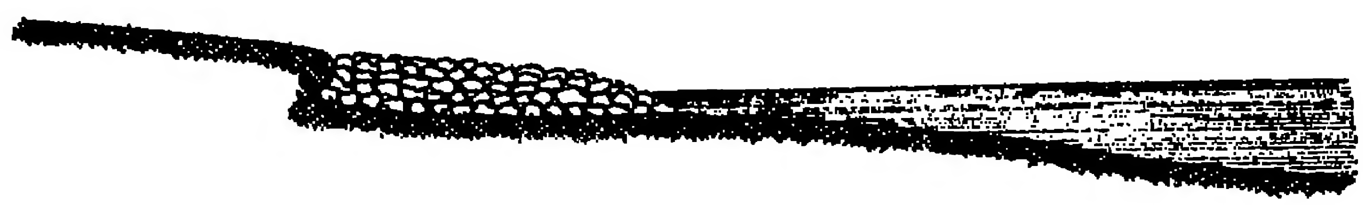


Fig. 123.—New southern icefoot, March, 1911.

On March 21, a strong gale blew from the south-east, and the heavy sea which accompanied it built up an icefoot of stranded floes and bergs and of brash ice and spray ice some distance above sea level. As the normal swell in calmer weather was unable to reach this new deposit and dissolve it, it persisted and formed the nucleus of the 1911 icefoot.

After the gale of the 21st, the temperatures rapidly decreased, and the sea began to freeze in earnest.

The immediate result of the fall of temperature on the icefoot was manifested in three ways:—

(1) A selvage of the frazil crystals which form the upper layer of the sea ice was washed up on to the icefoot and on to the beach by the slight swell.

(2) A tidal platform of the type shown in Fig. 104 began to form on the stranded floes along the icefoot.

(3) The boulders of the beach between high-and low-water level became coated with ice (Plate CCXIV).

The growth of this latter coating was not, as we had formerly believed, by the deposition of concentric layers of ice, but by the formation of blunt ice-prisms with pyramidal

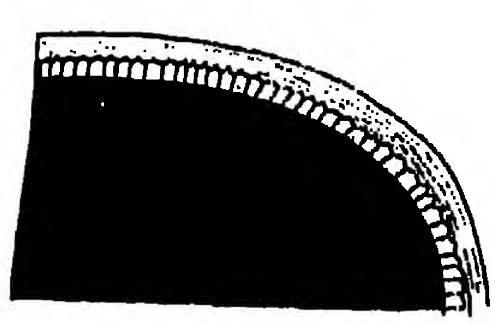


Fig. 124.—Ice sheathed boulder

Fig. 125.—Section through southern icefoot, April, 1911.

tops, which commenced to grow as rosettes here and there on the boulders (Plate LXXII, Chapter III). These spread rapidly, however, until the whole boulder was covered with the crystals (Fig. 124). After this complete covering had been formed, growth proceeded so quickly that all visible structure was lost. The final result was a uniform coating of ice, which had first much the appearance of the crust of a plum pie but which gradually lost this irregularity as it increased in thickness.

The southern side of the beach was thus completely sheathed in ice, and deposition went on slowly in the manner outlined above until the next storm. A diagrammatic section through the southern icefoot at this period would therefore be much as in Fig. 125, the component parts in April being :—

1. Snow-drift to the windward of the icefoot.
2. A wall of small rounded pieces of brash ice (Plate CCXV).
3. A line of stranded floes and small bergs (Plate CCXVI).
4. Either a tidal platform, if the bergs reached sea level, or an ice-swathed beach if they did not.

The ice boulders which made up the wall of brash ice on the shore side of the icefoot were singularly well rounded. When split open, they proved to possess a core of sea ice. Round this core was formed a layer from half an inch to an inch thick of very clear ice, which was altogether free from bubbles (Fig. 126). The outer layer might be the result of deposition from sea water while the block was being tossed about by the sea, or it might have marked the distance to which the sea water had been able to penetrate and fill up the air cavities in the original ice.

Although the main action of the gale had been one of deposition, the effect of the sea as a denuding agent had not been negligible, and the net result had been to remove the

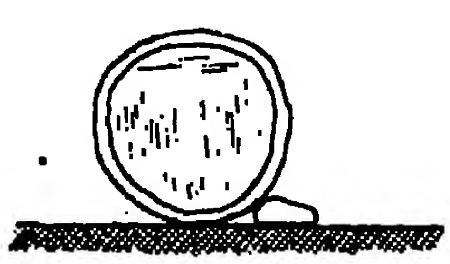


Fig. 126.—Sea-washed ice boulder.

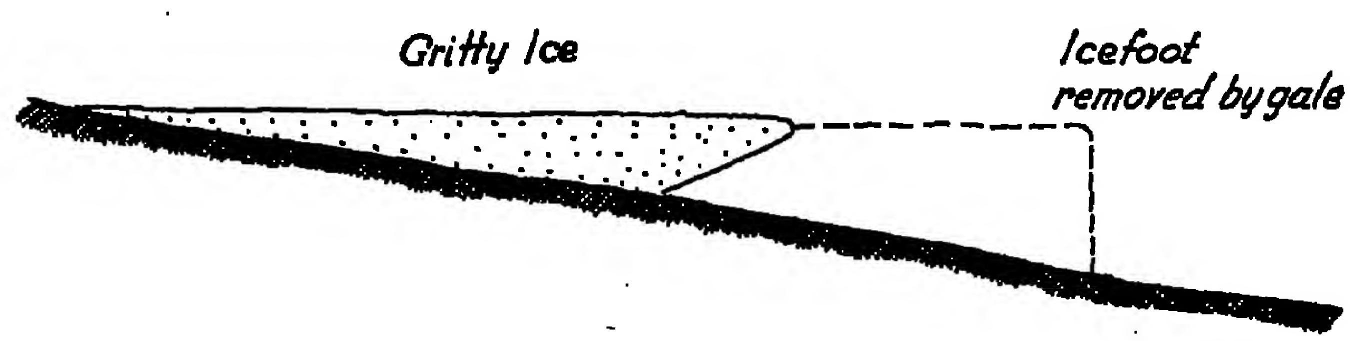


Fig. 127.—Section through last year's icefoot.

icefoot further up the slope of the beach, thus leaving room for an extension in width during the next calm spell. Fig. 127 shows a section through one of the many places where the effect of the gale upon the former icefoot was quite clear, and a deep bay had been cut into the old ice.

The edge thus left was often very much undercut by the sea; while the old ice, which was the result of some of last year's storms, was so full of basalt pebbles as to appear black, even in small fragments and in thin sheets.

This sprinkling of ice with gravel is quite a feature of icefoot-formation under surf conditions such as have just been described. When there is a noticeable swell, as there usually is at Cape Adare, a dark-brown strip of water always extends for 50 or 100 yards from the icefoot. This strip receives its colour from the fine basalt dust held in suspension in the water.

Mention should be made here of the occurrence of ice-forms similar to the type of pack ice known generally to the Expedition as "Swan-Ice." This ice occurred along the southern icefoot even so late as April. That the sea must have had some dissolving

action at that time was proved by the appearance of the narrow necks which characterise this type of ice.

Fig. 128 is a diagrammatic section of some of the small pieces stranded at the edge of the icefoot on April 6, at a time when the main action of the sea was certainly in the direction of deposition. It is possible that the water bathing the icefoot, having deposited comparatively fresh ice on the walls of the latter, was slightly more saline when it fell back into the sea, and was thus able to dissolve a certain amount of ice from the isolated boulders a short distance to seaward. Certainly these necks did appear, though they were at this time almost confined to fragments of ice lying in isolated positions to seaward of the main wall of the icefoot (Plates CCXVII and CCXVIII).

Fig. 128.—Swan ice at Cape Adare, April, 1911.

The stranded floes and bergs which have been mentioned as forming the second line of the new icefoot were already covered thickly with spray, and large masses of seaweed had been thrown up on them and frozen in. The spray ice was of a greasy white colour, and very full of air and salt, both of which seamed the ice as a network of anastomosing veins and gave to the storm icefoot its characteristic appearance. The spray was all deposited as rough bulbous crenellations, with ridges and troughs dipping steeply in the direction from which the wind blew (Plate CCIX).

During the next few weeks, the growth of the southern icefoot continued steadily—during calm weather by addition to the tidal platform, which increased in width until it commenced to fill up the spaces between the stranded floes and bergs (Plate CCXIX); and during gales, by the addition of spray and of beds of gravel, which was thrown on the lower portions of the icefoot (Plate CCXX). Thus, during a prolonged calm spell, it would increase noticeably in width; while, after a heavy sea had been at work for some time, the width of the icefoot would decrease sensibly owing to the removal of the seaward portions. This decrease in width, however, would be far outbalanced by the accompanying increase in height.

Towards the end of April, the sea ice began to remain in the bay, in spite of the onslaughts of the pack and wind. From now on, until the May gale, the pack was shut out of Robertson Bay, and the pressure of this heavy ice on the new ice of the bay caused the addition to the icefoot of heaps of pressure ice (Fig. 129).

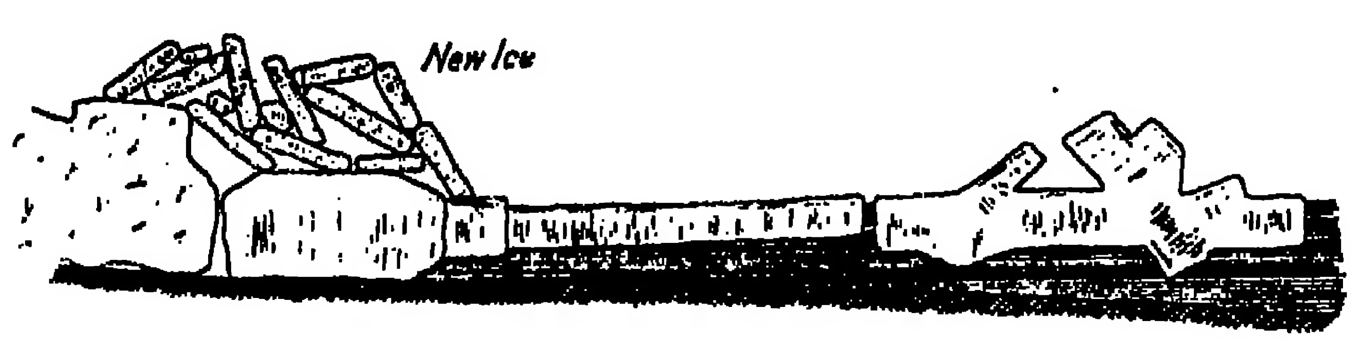


Fig. 129.—Pressure ice added to the icefoot in April, 1911.

This addition was partly permanent, though in many cases much of it was removed by the succeeding gale.

After the formation of the sea ice, the icefoot never grew much in breadth, for, as fast as the tidal platform widened, the extra width was removed, while still damp and

soft, by the trituration of the sea ice as it rose and fell with the tide. It is to the early formation of the ice in the bay that the comparative narrowness of this portion of the icefoot, compared with the width afterwards reached by the tidal platform along the northern icefoot, must be attributed.

THE "SOUTHERN" CLIFF ICEFOOT.

A similar sequence of events had marked the formation and growth of the southern portion of this icefoot, but, in spite of similar weather conditions, the latter took on an entirely different shape. This may be attributed to the shape of the portion of the beach on which it was formed. The screes fell sharply to the sea level from Cape Adare, and it was these steep screes that gave the predominant cast to the shape of the icefoot. Fig. 130 is a diagrammatic section through the new icefoot (Plate CCXX.)

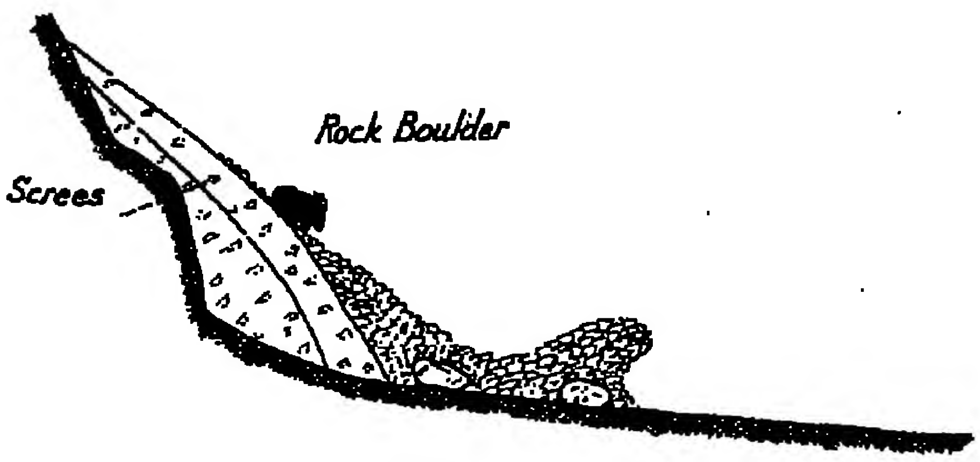


Fig. 130.—The southern cliff icefoot, April, 1911.

THE "NORTHERN" ICEFOOT.

The formation of the icefoot, at the northern end of the beach, proceeded in a markedly different way from that already described, and this difference was mainly due to the fact that the greater part of the spray from the swell, which was here the chief factor of deposition, was blown offshore as fast as it was formed. The sea produced by the southerly gales had little or no effect on this north shore, except in the single case of the May gale. Its absence, however, was more than compensated by the occasional action of a much heavier swell from the north, which was sufficient to hurl huge boulders containing many tons of ice some 20 or 30 yards beyond normal high-water mark (Plate CCXXI). The chief characteristic of the northern icefoot was undoubtedly these large rounded boulders of ice (Fig. 131), some of which were fragments of glacier bergs, but more of which were heavy pressure floes derived from the pack which was ever circling past the entrance to Robertson Bay. As these blocks had been covered by a certain deposit of ice during their bath in the swell in March, it was for some time impossible to gain any idea of their general structure, though the structure of parts of them was made out when ice was being taken for domestic purposes. It was not until much later in the winter—when ablation had removed 2 or 3 inches from their windward sides—that the structure of several of the largest was betrayed in detail

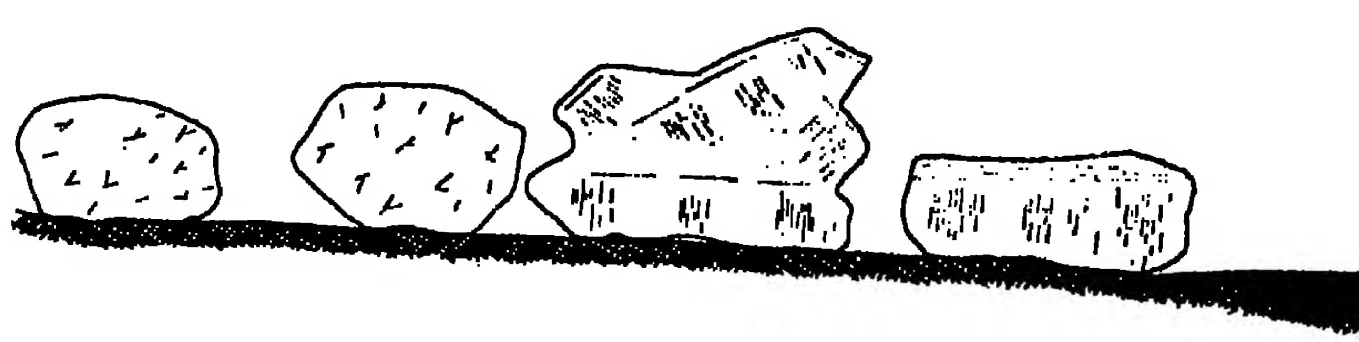


Fig. 131.—Ice boulders hurled by the swell on the northern icefoot at Cape Adare, March, 1911.

by the arrangement of the air-tubes and bubbles within them. Then we found, to our surprise, that these giant boulders, whose smallest dimension was, in some cases, as much as 12 feet, were often made up entirely of blocks of pressure ice cemented together with frozen spray and sea water.

The structure of one of the bergs in question is shown diagrammatically in Fig. 132. In spite of its origin, the ice was so fresh as to be readily used for cooking, and only the very slightest flavour of salt was to be detected by the most sensitive palate.

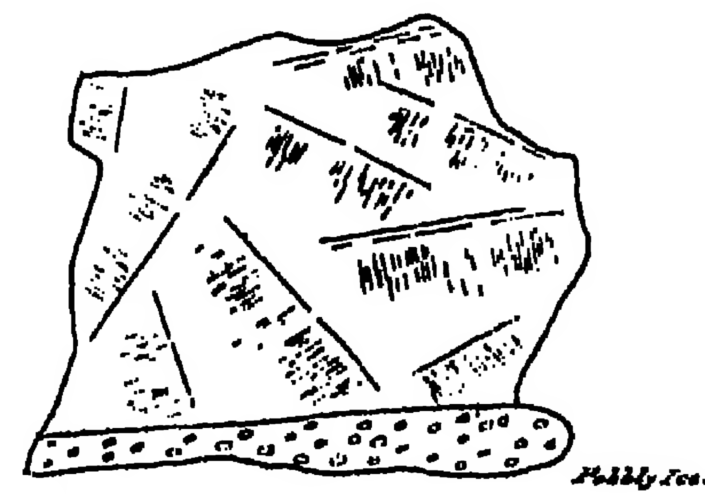


Fig. 132.—Structure of pressure berg.

The spaces between those boulders which had been thrown farthest up the beach were filled with gravel banks, heaped up by the same heavy swell and kept in position by the ice which formed a cement between the pebbles.

Spray-coated snow-drifts were also prominent, while a tidal platform of far greater width than that along the southern icefoot had commenced to form between high- and low-water mark, as in Plate CCXXII, showing the icefoot at Inexpressible Island. The formation of this platform was much aided by the absence of sea ice, which formed much later here than in the bay. Once formed, the icefoot was protected by the preservative action of several large floes which were stranded along the beach. It was also greatly extended by the growth outward from the shore of huge masses of the frazil crystals described in Chapter III, under the heading "Anchor-Ice."

In spite of one or two minor winds in April, the chief additions to the icefoot during that month took the form of increases to the width of the tidal platform, which only occurred in those places where the sea ice did not press too closely against the shore. On the 4th of May, however, the whole of the sea ice was removed by the opening gusts of the great ten days' gale, and, during the next ten days, the icefoot, both to the north and south of the beach, trebled, and even quadrupled, in size.

Very little has been said, so far, in this description, of the effect and the characteristic appearance of the frozen spray carried over the southern icefoot of the foreland by these blizzards; and this is best treated in connection with the present gale, when its effects were certainly most noticeable. During a gale from the east-south-east, the usual direction at Cape Adare, the wind blew rather off the icefoot than towards it. The effect of the spray at such times was, therefore, confined to the immediate vicinity of the shore, where steep deposits a few yards only in breadth were built up (Plate CCXXIII). During the latter part of the May blizzard, however, the wind swung suddenly to the south, and blew from that direction for several days, slightly less strongly than from the former quarter, but still with sufficient force to raise a heavy sea. The result of this change of direction was at once evident. The spray, instead of being blown almost parallel with the icefoot, was now carried directly inshore. During these three or four days, thousands of tons must have been added to the icefoot as "spray ice." From being formerly a comparatively narrow strip 20 yards wide at the most, the icefoot

rapidly spread shorewards until it encroached on the habitable portions of the penguin rookery. At the same time, all the greater depressions at the back of the high narrow storm icefoot of former days were filled with pools of slush, resulting partly from spray, partly from whole green seas which dashed over the outer wall.

The effect of the seas was equally well marked along the northern icefoot, for the offshore wind was practically powerless to stop the irruption of these huge waves which dashed over the lower portions of the icefoot and filled up the depressions within it. At the end of the gale, when the sea was falling, and it was possible once more to view the icefoot closely, there was no single feature, excepting only perhaps some of the largest stranded floes or bergs of particularly striking shape, that was recognisable as one of the former landmarks. All that was to be seen was an endless series of spray ridges and crenellations, while the effect of the sea spray spread far beyond the icefoot proper, even making itself felt on the cliffs of Cape Adare. To *windward* of nearly every projecting boulder on the beach, a small triangular deposit of spray, which was regulated in size by the size of the pebble, had formed (Fig. 113). The position of these triangular deposits is interesting, as showing that their presence is due to direct impact of tiny drops of half-frozen spray, as opposed to the deposition of snow-drift in the lee of similar projections.

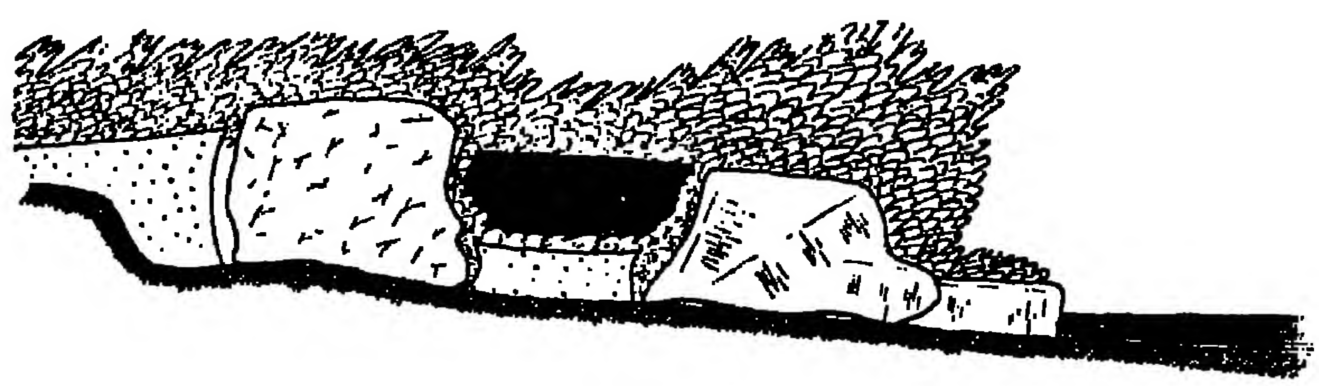


Fig. 133.—Section through southern icefoot, after the May gale.

The icefoot increased in height during this gale until it averaged from 8 to 12 feet thick behind the seaward boulders, while some of these latter where half as high again as they were before the gale. Fig. 133 gives some idea of the relative proportions added to the southern icefoot by spray ice and frozen sea water during this gale, while Fig. 134 is a section of the northern icefoot, showing four types of deposition which took place at the same time. The two methods of increase which have not yet been mentioned, and which are more interesting than significant, are the addition of large quantities of seaweed washed up on the seaward edge of the tidal platform, and the formations of drifts of fine sand to windward of all high prominences.

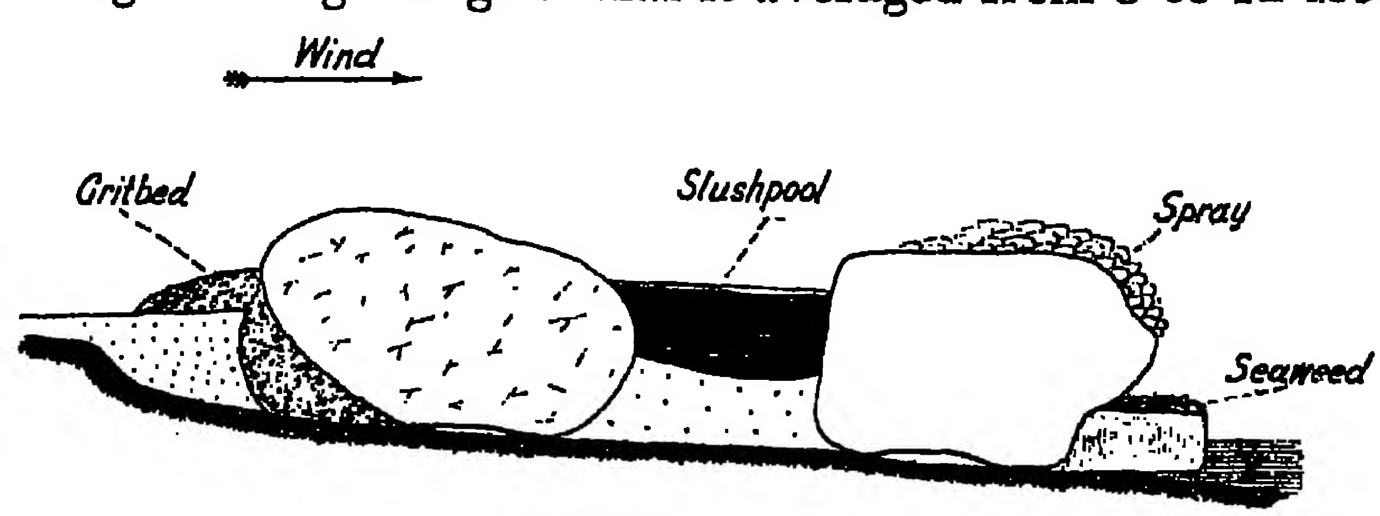


Fig. 134.—Section through northern icefoot, after the May gale.

One type of deposition on the icefoot, which was especially well developed during this gale, took the form of the large beds of small pebbles which have already been

mentioned as the last portions of the icefoot to disappear in summer. During the short April blizzards, beds of this type had frequently been deposited, but never on such a large scale as at this time. In the depressions at the back of the seaward bluffs of the icefoot, gravel beds 2 or 3 feet in thickness, and often many square yards in extent, were formed. These were immediately covered with frozen spray and slush, and hidden until ablation, denudation, and thaw had done their destroying work during the winter, spring, and early summer, when they once more appeared, to become favourite basking grounds for the penguins. Such beds were easily distinguished from the rest of the beach, by the uniform and small size of the pebbles which composed them and by their level surface.

In order to explain the occurrence of the grit beds in Fig. 134, it is necessary to refer to the second important influence which a strong wind exerts on the icefoot, if prolonged for any time. This is the ablative and drift-chiselling power of the wind.

The gales at Cape Adare were usually free from snow, except in their early stages; but such snow as did accompany the wind was carried along at such a speed that it had a disproportionate effect on the snow and ice-formations in the neighbourhood, while the gales were so powerful that a considerable quantity of rock dust and small

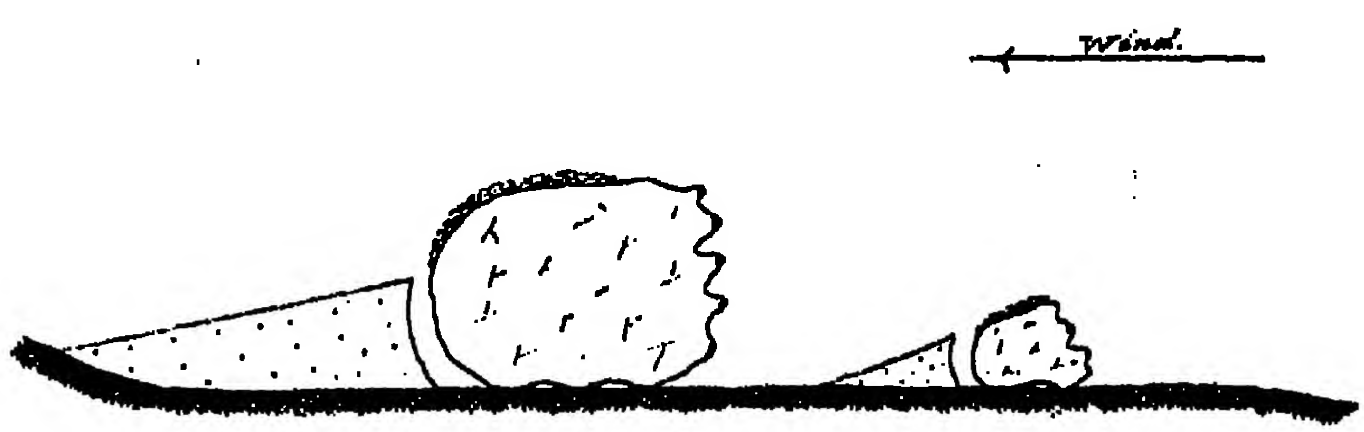


Fig. 135.—Examples of ablation effects of the May gale.

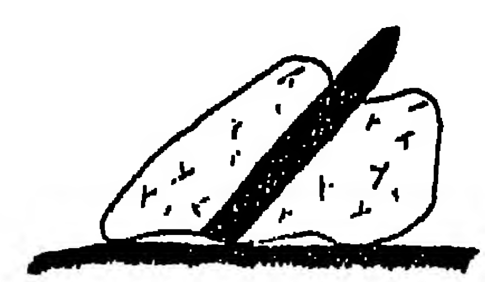


Fig. 136.—Weathered ice boulder, showing projection of grit-laden ice.

pebbles took part in the work of denudation. It was these last, in combination with similar rock dust obtained by concentration from the blocks forming the icefoot itself, that formed the deposits of grit shown in Fig. 134.

Even when the wind carried no visible drift, its effect was by no means small; for, everywhere, during and after such a gale, the signs of true ablation along the northern icefoot were very marked wherever they had not been masked by the deposition of spray ice.

Some examples of the effect of this process are seen in Figs. 135 and 136. They depend for their value on the fact that the ice of the boulders was not by any means of uniform constitution. In particular, Fig. 135 shows a boulder that had been lightly covered with spray ice and had then been exposed to the action of a powerful wind for some time. The result had been the etching of a series of ablation ripples on the windward side of the block, while, on the leeward side of the block, the outline remained comparatively unchanged. The effect of the ablation was particularly well shown at the stage when the figure was drawn, because the spray ice-covering had been removed everywhere, except from the summit of the ridges between the ablation troughs. The

white greasy appearance of the few remaining scraps of ice showed up remarkably well against the dark greenish-blue ice of the glacier boulder.

Another example of differential ablation shown in Fig. 136 may be attributed to the presence of layers of ice laden with grit in ice blocks which were mainly free from foreign inclusions. These blocks had come presumably from the remains of some former icefoot either here or elsewhere, and had been thrown up on the beach by the autumn swell and there frozen in. They had then gradually decreased in size under the influence of wind after wind, and to a less extent also in the calm spells between, and the grit-filled beds had weathered less quickly than those of pure ice. The former had thus been left projecting out of the ice, giving the impression in some cases of a bed of loosely-coherent volcanic tuff.

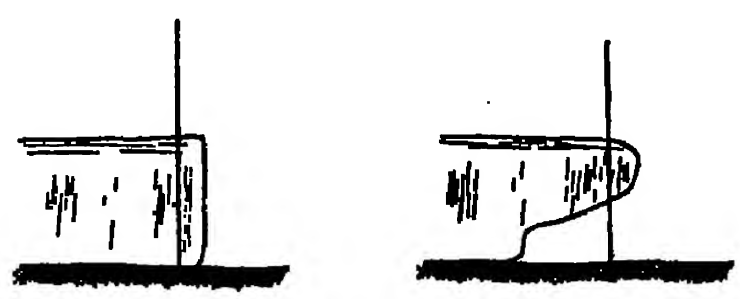


Fig. 137.—Denudational effect of heavy sea.

Yet another effect of the ablation was particularly well seen in the case of the boulders at the northern end of the northern icefoot. These were hurled up the shore of the beach at the time of a most tremendous swell, and they lay opposite to a part of the beach which was composed of much smaller material than was to be found at most places. A good deal of this fine grit had been thrown over the blocks and frozen into them during the time they were bathed in the swell. The boulders at this portion of the icefoot were therefore quite dark in colour, owing to the included grit. Now that they had been exposed to the wind for some time, they had quite an irregular surface, the grit standing out all over them as little angular projections.

Lastly, the denuding influence of the sea produced by the gale should be mentioned. This manifested itself clearly in the partial destruction of the tidal platform, wherever the latter did not rest directly upon the gravel or boulders of the beach, and in the undermining and removal of prominent points of the icefoot. Where, however, the tidal platform did rest directly on the beach, it usually resisted the action of the waves. The only result the sea then had upon it was to absorb it into the storm icefoot by the deposition of brash ice, pressure, and spray upon its flat surface.

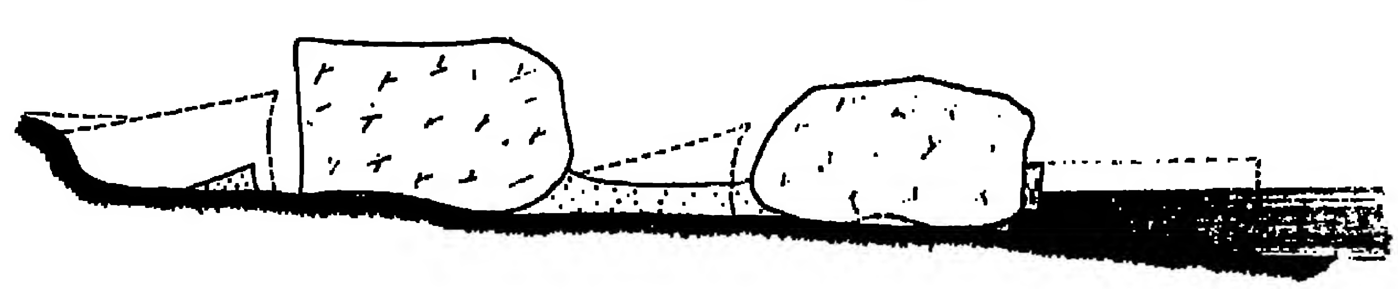


Fig. 138.—Generalised section through the northern icefoot, to illustrate denudation processes.

At the end of the gale, the tidal platform, as such, certainly appeared to have gone, but in most cases it still existed in the interior of the new icefoot. Fig. 137 illustrates this denudational effect of the sea on the tidal platform particularly well. It is a section through the latter before and after the gale at Tidepole Cove, where the relative advance and retreat of the ice was shown up by its relation to the pole by which the rise and fall of the tide was measured (Plate CCXXIV). The figure shows the effect of the first day's sea. It is easy to see that at the end of ten days very little of the tidal platform might exist in exposed places. A generalised section of the northern icefoot, showing the effect of the different denudation processes, is seen in Fig. 138.

The undermining action of the sea was also quite effective. By a combination of "assault and battery" and solution, the tidal platform which had been formed between the stranded bergs right within the body of the icefoot would suddenly be broken through. and a "blow-hole" formed such as may be seen in many of the rocks of our own coast. Through these "blow-holes" would be hurled large quantities of water, brash ice, seaweed, &c., and thus portions of the icefoot, which would have been protected from the direct action of the waves by the bulwark of the seaward boulders and spray-covered drifts between them, were speedily filled with ice and pebbles. It was in the neighbourhood of such holes that the majority of spray ice which was to be found on the northern icefoot occurred.

Another method by which similar holes were formed was, of course, by the widening of the tidal platform, growing outwards from three or four bergs near to one another.

Changes in the Icefoot during the Winter.

Immediately after the cessation of the May gale, the ice formed again in Robertson Bay; and this time it remained fast until the next summer. No further change took place in the manner of growth of the southern icefoot, and the chief visible modifications were those due to pressure and to temperature changes.

Along the northern icefoot, on the other hand, the strong tides managed to keep a comparatively clear space for a week or ten days. Here, with the low winter temperature, the tidal platform grew seawards with extreme rapidity and with great regularity, reaching a width of over 20 yards in places. This platform became decidedly the most characteristic feature of the northern icefoot during the course of the winter, for its growth was much helped by the fact that three or four of the winter gales removed the sea ice from along this shore of the beach, and thus permitted fresh growth along the icefoot.

The sole other method of increase in the size of the icefoot during the winter months was an insignificant deposit of hoar-frost—a deposit which has not been mentioned before because its effect during the spring and early winter was more than neutralised by the ablating influence of the wind. The calm winter months, however, were frequently marked by a saturated atmosphere, which was probably due to the continued presence, of open water to the north and east. The hoar-frost, though relatively insignificant in amount, gave rise to several distinct phenomena, amongst which the formation of ice-flowers along the seaward edge of the icefoot was perhaps the most striking. A heavy deposit of crystals on the icicles of a cave in the icefoot is shown in Plate LXXXIX.

Much might be said, also, about the formation and modification of the icicles which fringed the icefoot here and elsewhere. An icefoot, facing as it does on an open sea, and subject as it is to the effect of spray, tides, and swell, must necessarily be a peculiarly favourable stituation for the study of different forms of icicles.

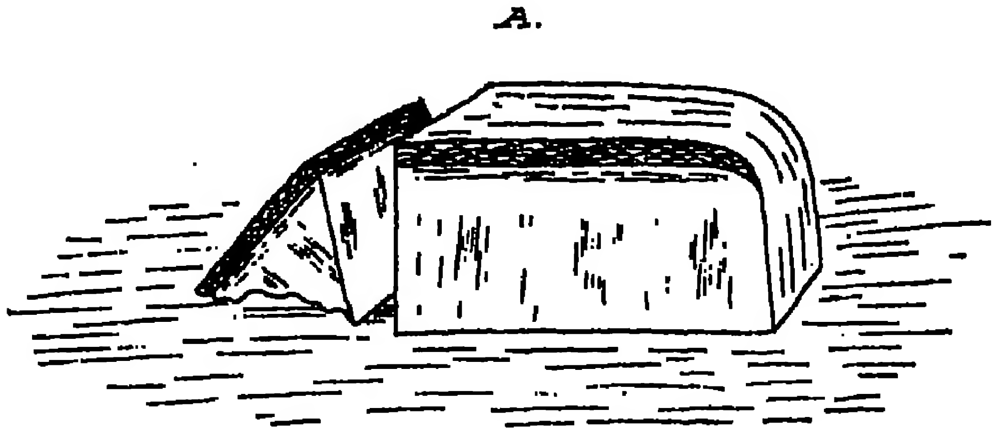
These have, however, been fully dealt with in the section on icicles in Chapter III. Some of the photographs which illustrate the present chapter will be seen to show icicle-

formation, and, in many, the characteristic bluntness of outline and the fantastic shape of salt-water icicles and their drift modifications are well portrayed.

Changes in the Icefoot due to Temperature and Pressure.

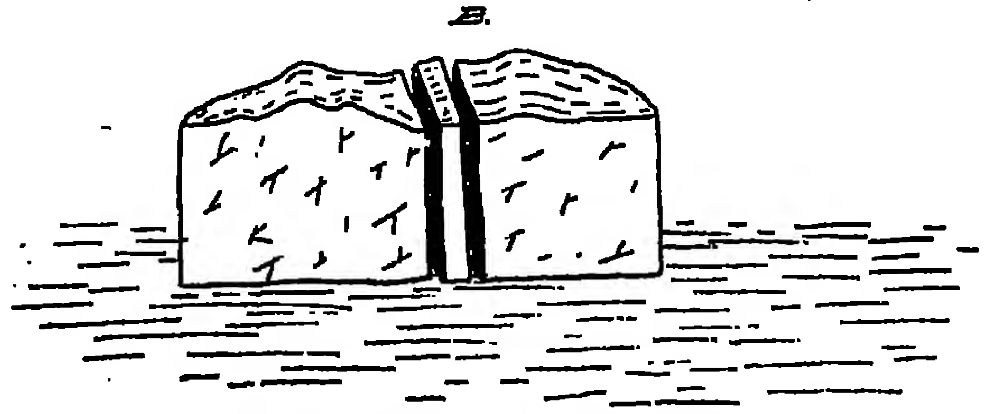
The result of a sudden change of temperature on the icefoot is well seen in Plate CCXXV, while similar split blocks are shown diagrammatically in Fig. 139. The most noticeable cases occurred when large boulders had been undermined by the action of the heavy sea during the April and May gales. The overhang of the seaward end of the boulders would be emphasised by the accumulation of huge masses of sea spray upon them, and there seems no doubt that in some cases the weight of this superincumbent load of spray ice was in itself sufficient to cause the fracture.

A.



Boulder split by temperature changes.

B.



Similar effect on another block.

Fig. 139.

Strain cracks began to appear, however, in many of the stranded bergs along the icefoot to which this explanation would not apply. These must be directly attributed to the influence of sudden changes of temperature, an agency which was probably not ineffective in hastening the fracture of the overhanging blocks.

The arrival of these cracks usually coincided with the fall of temperature at the close of a blizzard, a sudden fall which also had disastrous effects on the neighbouring snow-drifts, especially when, as in Fig. 140, the latter had been weakened beforehand by a change in direction of the drift-bearing wind causing holes to be drilled through the snow-drift.

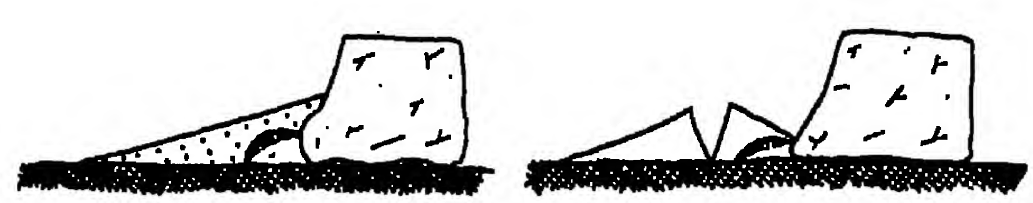


Fig. 140.—Effect of temperature change on snow-drift.

The formation of the new sheet of sea ice in Robertson Bay, after the May gale, was followed by several days of light westerly wind which appeared to be associated with strong westerly gales to the north. This was fully borne out by the behaviour of the pack. The latter must have been swept some distance northwards by the strong southerly wind at the commencement of the month, and its absence gave the new sheet time to form and grow strong.

It now returned swiftly and piled itself up against the seaward edge of the Fast-Ice, producing a chaos of pressure ice near its junction with the latter. A wedge of the pack then forced its way right into the bay, with the result that the ice in the latter

was pressed eastwards and westwards, and was piled in huge masses on the icefoot at Cape Barrow and at Cape Adare. With such force did the irruption take place, that many of the blocks of the Ridley Beach icefoot were tilted considerably out of the perpendicular (Fig. 141), while, in one or two cases, the top portion of a block was sheared right off, as in Fig. 142. (Plate CCIX.)

The pressure ice left on the icefoot was, however, never cemented together by sea spray, and so was not incorporated permanently in the icefoot, being easily detached when the sea ice broke up in the middle of the following summer.

Mention has already been made of the draining of salt from the blocks stranded along the icefoot, and of the gradual change in the internal structure of the ice of some of these blocks. Both changes continued throughout the winter, the former being much facilitated by the high temperatures which prevailed in the blizzards, while the latter change was most noticeable in the outward growth of the granular structure of the ice of glacier blocks into the spray covering which surrounded them. The only other change worthy of notice which occurred before the summer temperatures set in was the stranding of one or two fair sized floes along the northern icefoot, and their

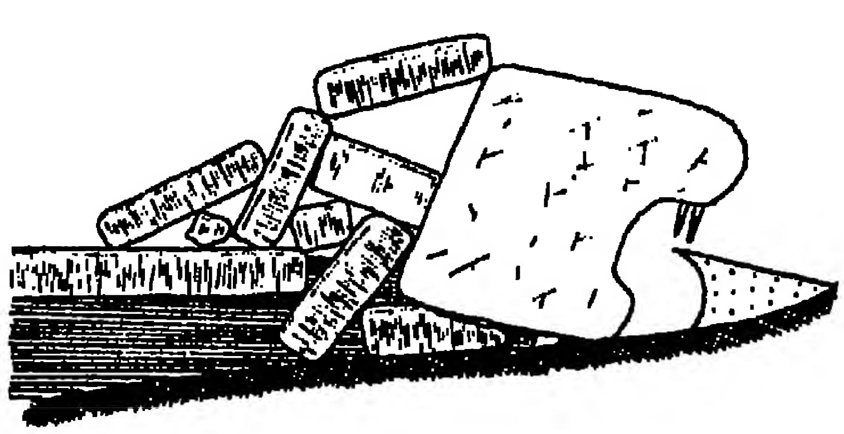


Fig. 141.—Block tilted by pressure.

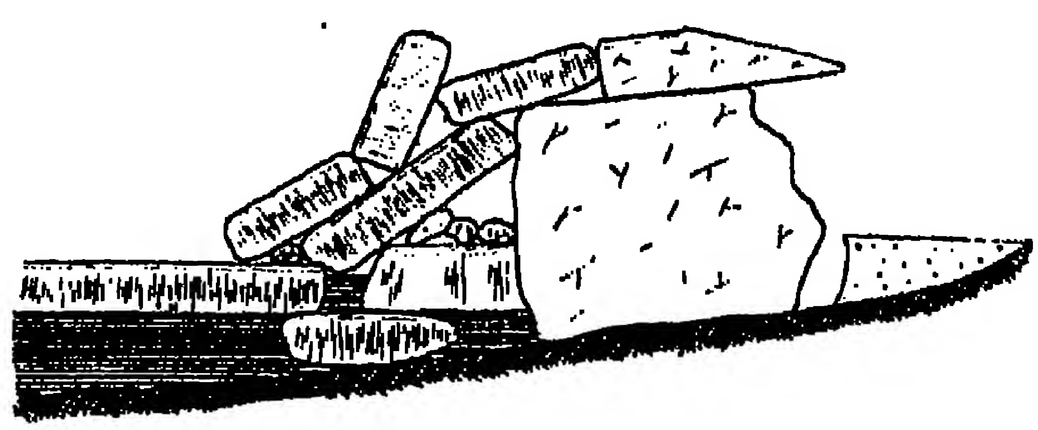


Fig. 142.—Portion of ice block faulted off by pressure.

incorporation in the steadily growing tidal platform. This took place at those times when leads were opened during the July and August hurricanes.

Summer Changes in the Ridley Beach Icefoot.

During the spring and early summer, sledging parties were constantly absent from the beach for a week or a fortnight at a time, and, on their return each time, an examination of the icefoot was made. For some weeks after the sun had returned, however, the only way in which its influence could be traced was in an increase in the number of icicles depending from the overhanging portions, and in a slight speeding up of the rate of ablation everywhere. No marked change, and especially no marked thaw, was observed until the beginning of November. A gradual blackening of the icefoot, owing to a concentration of the grit contained in those portions of it which had been formed during storms, and a dwindling and rotting of the spray ridges along the southern icefoot, were the most noticeable features of its slow decay.

After the beginning of November, however, the sea to the north of the beach began to open up, and the influence of the sun on the water to make itself felt; while, at the same time, its direct influence on the icefoot began to be really destructive. The effect

of the sea water was soon seen in the undermining of the tidal platform and its gradual crumbling from the seaward edge, while the general effect of the thaw is well described in a note made on November 23 :—

> " The northern icefoot is only a shade of its former self. On the seaward and sunny side the boulders are all deeply corrugated and pitted by the thaw. All the snow drifts are rotten, and give way under the foot; while in every depression is a pool of yellowish brine, discoloured by the drainage from the penguin rookery. The latter are thinly iced over, and are in places 2 or 3 feet deep."

A good idea of the appearance of the summer outline of the icefoot at this stage, as compared with its spring outline, is given by Fig. 143, in which the dotted lines represent the spring outline.

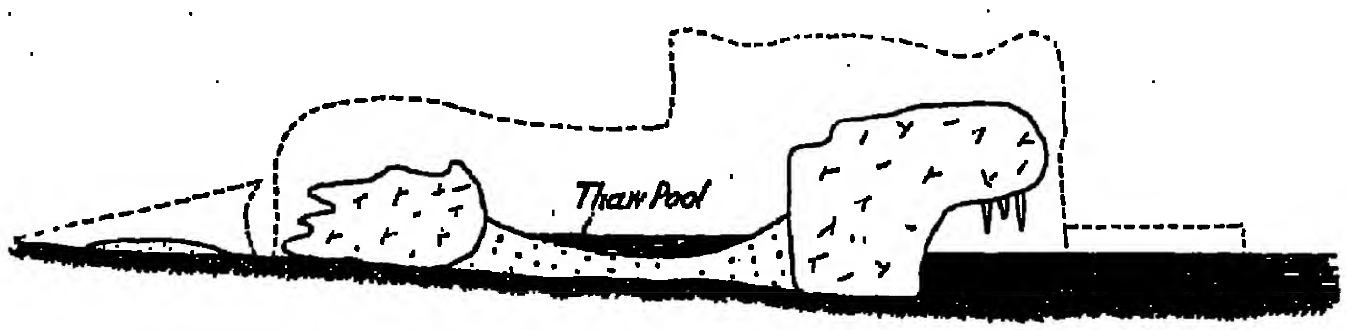


Fig. 143.—Spring and summer outline of the icefoot contrasted.

After it had once started, disintegration proceeded apace, and the work of the sea and the thaw was much aided by the streams draining off the beach. These were warm and heavily charged with salt, and rapidly cut channels for themselves through both storm icefoot and tidal platform. The icefoot was everywhere liable to give way under an unwary footstep, letting one down into pools of brine, while it was everywhere divided into segments by the streams cutting across it from the beach behind.

As the icefoot thus dissolved, large rotten pieces would continually fall from its seaward edge. Once the sea ice had left the shore free, the pack once more swept past the beach, and the big floes ground along the shore and carried off huge pieces of the icefoot.

By the time the Northern Party left Cape Adare in January, 1912, the 1911 icefoot was in truth but a shadow of its former self. Its subsequent history can easily be inferred from our experience elsewhere in the Antarctic, and from the appearance presented by the previous year's icefoot in February, 1911.

Geological Significance of the Antarctic Icefoot.

Apart from the importance of the icefoot to sledge parties travelling round the coast, the formation has a highly significant geological effect. From this point of view alone, a detailed description of its life-history is justified. A similar ice girdle must surround such portions of the coasts of lands within the Arctic circles as are not fringed with glaciers, though it seems unlikely that the Arctic icefoot is so persistent as that which borders Antarctic lands.

The chief geological effect of the icefoot is undoubtedly the conservation of the coast to which it is attached. The only months in which, normally, wave erosion can take

place along the shores of the Antarctic continent, are February, March and April. Very seldom will the icefoot have been entirely removed in January, or not have recommenced to form before May. While the icefoot is present, the abrading influence of the waves is largely expended upon these semi-permanent deposits, and erosion by wave action is reduced to a minimum. It is, indeed, only in peculiarly favourable situations (as will be seen in the Physiographical Memoir)* that wave erosion plays any important part at all in sculpturing the present Antarctic coastline. Almost everywhere its effects are either absent, or masked by the speedier action of other agents of denudation.

The icefoot thus exercises a profound influence upon the rate of denudation of the coasts which it borders.

Less conspicuous, but possibly even more far-reaching in its consequences, is the work carried out by portions of the icefoot as a rock-transporting agency. In extent, the action of the icefoot in this way is probably less important than that of sea ice, for most of the rock fragments carried on blocks broken off an icefoot will be deposited comparatively near their place of origin. Occasionally, however, blocks of considerable size must be carried many hundreds of miles along the coast.

Very fine examples may be cited from the experience of the present Expedition. The Northern Party found on the shores of Inexpressible Island, in Terra Nova Bay, several large fragments of kenyte. There is no reason to suppose that this particular rock occurs *in situ* any nearer than New Harbour, some 200 miles further down the coast. Indeed, it is practically certain that kenyte does not exist at any place, much closer than Ross Island, from which these blocks could have reached their present position.

From their occurrence near sea level, on what is undoubtedly a raised beach of waterworn boulders, the evidence is overwhelmingly in favour of their having been carried to their present position either by sea ice or by blocks of icefoot which have been brought north by the Ross Sea current, caught up in the eddy in lee of the Drygalski Ice-Tongue, and then stranded upon the beach.

It is an interesting—though entirely fortuitous—fact, that the rocks which afford such strong evidence of the transporting effect of floating ice are genetically allied to the "rhomb porphyry," which has played such an important part in the controversies which have sprung up around the subject of the European glacial period.

Certainly, these kenyte boulders could not have been carried to their present position by an extension of the Ross Barrier, or its former western component, the predecessor of the Koettlitz Glacier, which is responsible for the presence of the high-level moraines on Ross Island. No conceivable circumstances could be imagined which would have enabled this ice from the south to override or thrust aside the predecessors of the Drygalski Ice-Tongue, the Hell's Gate Piedmont, and the other great glaciers which flow down the valleys of the Antarctic Horst at this point. All the erratics which have been left on the heights of Inexpressible Island are rocks quite clearly derived from the mountains to the west. From the height at which these erratics occur, it is clear that there must have been a great increase in the volume of the ice pouring away

* "Physiography of the Robertson Bay and Terra Nova Bay regions of South Victoria Land." R. E. Priestley.

from this coast at approximately the same time as the maximum of the great ice-flood further to the south.

Further evidence of the transporting action of the icefoot, and of the effect this action must have in "mixing" geological deposits, was afforded by the incorporation in the ice-foot at Cape Adare of blocks quite clearly derived from the icefoot of the previous season and from some other portion of the coast. These blocks were crowded with gravel and larger rock fragments, and when they were melted in the summer, these foreign fragments were added to others on the beach. Such action, repeated an infinite number of times, may go far to account for the much larger proportion of rock of foreign extraction present in the beach deposits at the Cape than occurs on the peninsula itself, though a more probable explanation is advanced elsewhere in this memoir.

Deposits of rock formed under "icefoot" conditions were not frequently seen, owing to the absence of shallow-water conditions along the coast of Victoria Land. Where such deposits did occur, however, as at the beach at Cape Adare, they were of significant size. It is not claimed that the Cape Adare shingle and gravel spit was formed through the agency of the icefoot, but certainly the greater portion of the material has been re-sorted by this agency, and the surface features of the beach foreland can be plausibly attributed to the action described in the foregoing pages.

This question will be more fully described in its proper place. The fact is, however, significant in the present connection for, geologically, the most interesting feature of the study of the present ice conditions in both Arctic and Antarctic lands and seas, is the possibility thus opened up of drawing inferences as to the conditions under which older deposits were laid down.

The characteristics of beach gravels laid down and re-sorted under icefoot conditions should be :—

(1) A somewhat undulating surface.
(2) Extremely diversified examples of false bedding.
(3) The intercalation of beds of small material with others of much larger material.
(4) The presence of pockets and lenticules of sand.

Contortion would usually be absent altogether, though faulting of the deposits might complicate the structure on a small scale. In this absence of contortion might be found the most likely criterion to distinguish such deposits from those formed in the body of, or in front of, advancing glaciers. The outstanding feature of the conditions under which an icefoot is formed, is the absence of any large force acting for a long time in one direction at a slow enough speed to enable the ice to adjust itself by molecular rearrangement or by regelation.

Movement would either be absent, or would be such as to cause fracture, examples being the impact of pressure ice or floes, or the hurling of blocks of ice against the icefoot by a heavy swell.

CHAPTER X.

ANTARCTIC FAST-ICE.*

(A) *Methods of Formation.*

(1) First Growth.

The initial stages of the formation of sea ice in the Antarctic may be seen at any period of the year.

The "Terra Nova," in her passage through the pack in the middle of the summer of 1911–12, encountered large sheets of fresh "black" ice a very few inches thick, which had evidently formed between the floes and on the "leads" of open water during the last calm spell. Later, on her arrival in McMurdo Sound, the ship's way was completely stopped, when still some distance from the last year's ice, by an expanse of similar new ice, which increased in thickness as the old ice was approached.

These ice-sheets formed during the summer months are, however, evanescent. They may be remelted by a slight change in atmospheric conditions within a few hours of their appearance. If they survive for a sufficient time to become coherent, they are invariably, so far as our experience goes, broken up into "floes" and carried off to the north by the wind and current, and are then speedily melted by the summer sun of lower latitudes.

It is not until the late autumn that the sea ice* begins to show signs of persistence, and it is at this time that the methods of formation are best studied.

The first indication of the freezing of the sea is the complete obliteration of the minor rufflings of its surface, so that large tracts assume a greasy, oily appearance. Under favourable conditions the scum of ice crystals which causes these calm patches spreads, until the whole sea within sight is tranquil. If a bucket of water is drawn from the sea at this stage the water is seen to be covered with a free-floating layer of small plates of ice. These crystals are flat, about $\frac{1}{4}$ inch to $\frac{3}{4}$ inch across, and less than $\frac{1}{16}$-inch thick (Fig. 29, Chap. II). The first-formed crystals lie horizontally on the surface of the water. Plate CCXXVI shows the appearance of a sheet of young "black" ice formed under calm conditions.

* Sea ice definitions will be found in Chapter XI, on "Pack-Ice."

If the sea remains perfectly calm, the sheet of ice thickens gradually from below, the crystals becoming closely cemented together so that, after a lapse of 48 to 72 hours, the ice may become sufficiently strong to bear the weight of a man.

Should the sea be under the influence of a swell at the time of freezing, the sheet formed is at first sufficiently plastic to give to the movement. The long undulations of the swell, although diminished in amplitude, can still be very definitely discerned in the ice sheet. The appearance of the sea at such times has a close resemblance to that of a field which has been allowed to lapse into pasture land after having been ploughed for many seasons.

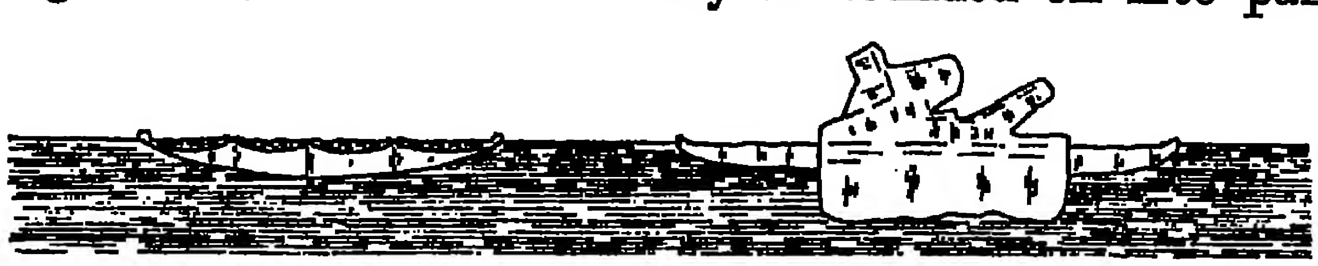
As the ice sheet thickens, it becomes less and less plastic, until finally the whole mass may be broken up into small angular pieces by the swell. These, rubbing against each other with the movement of the water, have their angles ground off and their edges turned up, forming the "pancake ice" which is such a feature of the Antarctic seas in the autumn and winter (Plates CCXXVII and CCXLVIII).

An extremely pretty example of the formation of a pseudo-pancake ice is often seen where drift is blowing off the face of an ice-cliff into the sea. This drift, provided the temperature of the water is low enough, forms into miniature pancakes, which are frequently no more than 1 inch in diameter, but which act exactly as do their larger relatives.

The part played by such drift in the formation of sea ice is by no means negligible, and, off the ice fringe which borders so large a portion of the Antarctic Continent, it must have an appreciable effect in advancing the date at which the sea becomes frozen over in the winter, and still more in increasing the amount of ice which forms during the late autumn, only to be broken up and driven north by the autumn gales (Plate CCXXIX).

On February 19, 1908, the "Nimrod" was undoubtedly preserved from destruction by the fact that she steamed into an area of this slush which considerably reduced the size of the waves with which she had to contend.

The component cakes of pancake ice vary greatly in size, but usually they are between 1 and 2 feet in diameter. Several of these smaller cakes may unite to form larger floes, which in turn may be rounded off into pancake form (Plate CCXXX). Another heavy type of pancake frequently met is formed by the growth of new ice round a nucleus formed by an old "hummocky" floe (Fig. 144). The size of the normal pancakes is evidently dependent upon the thickness reached by the ice before it is broken up by wave action.



Compound pancake. Pressure-floe pancake.

Fig. 144.

If the cold weather holds and the ice is not driven out by wind, the water between the pancakes next freezes and a continuous sheet is formed. From now on, growth becomes normal for calm conditions. That considerable stretches of sea ice owe their

origin to this process is clearly shown later in the year, when ablation has emphasized the structure of the ice.

At first the sea only freezes over under favourable conditions, but as the year advances and this first-formed ice is removed by the violence of the winds, the work is re-done under much more frigid temperature conditions. As the temperature falls, even the strongest winds only succeed in opening the sea for a period of time strictly limited by the duration of the gale. Directly the wind drops, the ice crystals already present increase in number, and cohere, and the sea rapidly calms.

Striking examples of this phenomenon occurred after each of the more important gales at Cape Evans and at Cape Adare, and two typical cases which occurred at the latter place may be cited here.

At 8 a.m. on the morning of April 20, the sea had been swept clear of ice by a southerly gale and the wind had ceased. By noon, the new ice crystals had frozen together; small pancakes had formed; these had had their edges ground up, and had in their turn been cemented together. The bay was covered to the westward as far as the eye could reach with a continuous sheet of ice 2 or 3 inches thick. The air temperature during this time had varied between 3° F. and 5° F.

On May 4, a hurricane again removed all the sea ice from Robertson Bay. The gale continued without intermission until the 10th, when it moderated for a few hours to a strong breeze. At 11 a.m. on the 10th, a heavy sea was breaking all along the southern icefoot of Cape Adare, but by 2 p.m. the sea was covered with a thick coating of ice crystals. Only a slight heaving under the ice testified to the recent roughness of the sea. The air temperature on May 10 had a mean as high as +16° F., but the winter was then so far advanced that considerable cooling must have taken place in the main body of the sea water.

One abnormal method of first-growth in sea ice is to be seen taking place in any holes which have been opened in the older sea ice by movements of the pack. The new ice crystals are carried against one edge of the older ice by the current, and the fresh sheet grows outwards from that side of the hole (Fig. 145). This method of growth was also observed in the waterholes off Hut Point in April, 1911, but the effect was probably accentuated by the small wavelets caused by the wind.

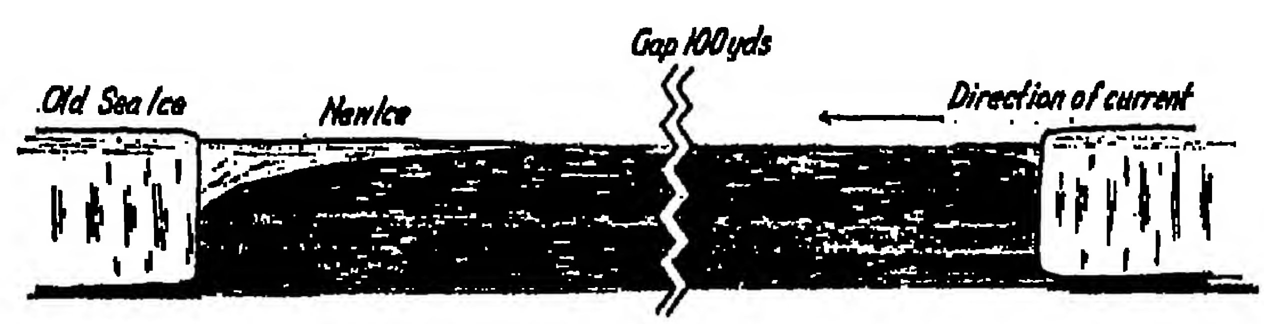


Fig. 145.—Growth of new sea ice in "waterhole" in the pack.

Rough observations were made of the rate of formation of the new ice at Cape Adare, but the only place where accurate measurement was possible was at the surface of the fish-trap hole, which had to be cleared before the trap could be raised or lowered. Here, the presence of thick older ice all round the new ice modified temperature conditions and probably increased the rate of growth.

The following table gives the measurements it was possible to make before the break-up in June removed the ice from within reach. The time which elapsed between observations and the mean air temperature during the period are also shown:

TABLE XII.

Date of observation.	Thickness of new ice.	Time elapsed since commencement of growth.	Uncorrected mean air temperature.
	Inches.	Hours.	° F.
May 5	4 to 5	48	+ 0·4
May 29	1 to 2	4	−25
May 30	$3\frac{1}{2}$	18	−21
June 3	6	72	− 1
June 5	4 to 5	48	− 6
June 9	$7\frac{1}{2}$ to 9	96	−11
June 11	6	48	−20
June 12	4 to 5	24	−19
June 14	6	48	−16

In July and August, the speed of formation of new ice appeared to be quicker, but no complete observations were made.

The formula derived by L. V. King, which is stated to be applicable to the rate of growth of a sheet of fresh-water ice, may be put in the form :—

$$(x+h)^2 = \frac{2\kappa}{\rho L}\int_0^t \theta \, . \, dt + h^2,$$

where θ = air temperature,
x = thickness of ice,
t = time,
L = latent heat of fusion,
ρ = density of ice,
κ = thermal conductivity of the ice,
h = a constant depending on the efficiency of the heat transfer between ice and air.

No allowance is made in this formula for variations in the rate of growth due to percentage humidity, wind velocity, or direct radiation, except in the inclusion of the constant h. Of these factors, the effect of the last is probably not large, and we have no exact information in regard to the probable magnitude of the heat transfer due to evaporation from the ice surface. Wind velocity, however, is clearly a factor of some importance.

We have already seen that the amount of ablation of an ice surface is dependent, not only on the air temperature, but also on the wind velocity. In fact, under the conditions obtaining in the Antarctic, the loss by ablation with free exposure to the air was about proportional to the square of the wind velocity. The transfer of heat due to this cause results, therefore, in an accelerated growth below directly due to the loss

by ablation above. As the latent heat of vaporisation of ice is much greater than the latent heat of fusion of ice, it seems clear that any loss by ablation on the upper surface is compensated to a greater or less extent by growth below. The amount of growth below corresponding to a given loss from the upper surface will depend chiefly on the boundary conditions at the surfaces water-ice and ice-air and the water temperature.

The rate of growth of the ice will depend upon the wind velocity in still another way. In calm weather, it is clear that the air temperature very close to the ice surface will differ from the air temperature some distance above the ice, and it is probable that the heating effect of the warm ice layer will extend a short distance into the air above the ice in calm weather. No pronounced difference will obtain during high winds, so it is clear that any rigorous formula for the growth of sea ice should include a term which would be equivalent to the interposition of a layer of poorly conducting material between the ice and the cold atmosphere, the thickness of this layer being some function of the wind velocity—great for zero wind velocity and small for large wind velocities.

As pointed out by King, the formula given above allows the deduction that, for water temperatures above freezing-point, the ice cannot exceed a certain limiting thickness, depending upon the air temperature. We have every reason to believe, however, that these conditions never obtain in the Ross Sea area; before the limiting conditions are reached, the water temperature is so much lowered that it is effectively at freezing-point or below. In the latter condition, the sea is full of frazil crystals, which are deposited on the under surface of the ice-sheet, in amount more or less independent of the temperature conditions of the air above. No limit can be put to the growth of sea ice in these conditions—a point of very great importance, as will appear later.

From the above discussion, it will be clear that any formula which will rigorously represent the rate of growth of sea ice will be an exceedingly complicated one, and that, in the present state of our knowledge, any formula which we may derive can only be a rough approximation. It is certainly of interest, however, to examine to what extent the formula given above fits the experimental data which is available. Though numerous observations were made at Cape Evans on the thickness attained by the sea ice, only one series up to considerable thickness (1911) is available, since, in 1912, the ice never persisted for any length of time. Generally speaking, the formula fits the experimental data fairly well, until the thickness of the ice becomes considerable, after which the ice increases in thickness at a greater rate than that given by the formula. It is considered that this is probably due to the deposition of frazil crystals on the under surface of the ice-sheet, which only takes place in the late winter and early spring. For small thicknesses of ice and early winter conditions, the formula seems to fit the facts fairly closely.

The curves showing growth in 1911 and 1912 at Cape Evans are given in Fig. 146.

(2) Subsequent Growth of Sea Ice from Below.

After the skin of ice has been firmly cemented and has quieted the movement of the water, the growth from below mainly consists in the addition of bundles of plates

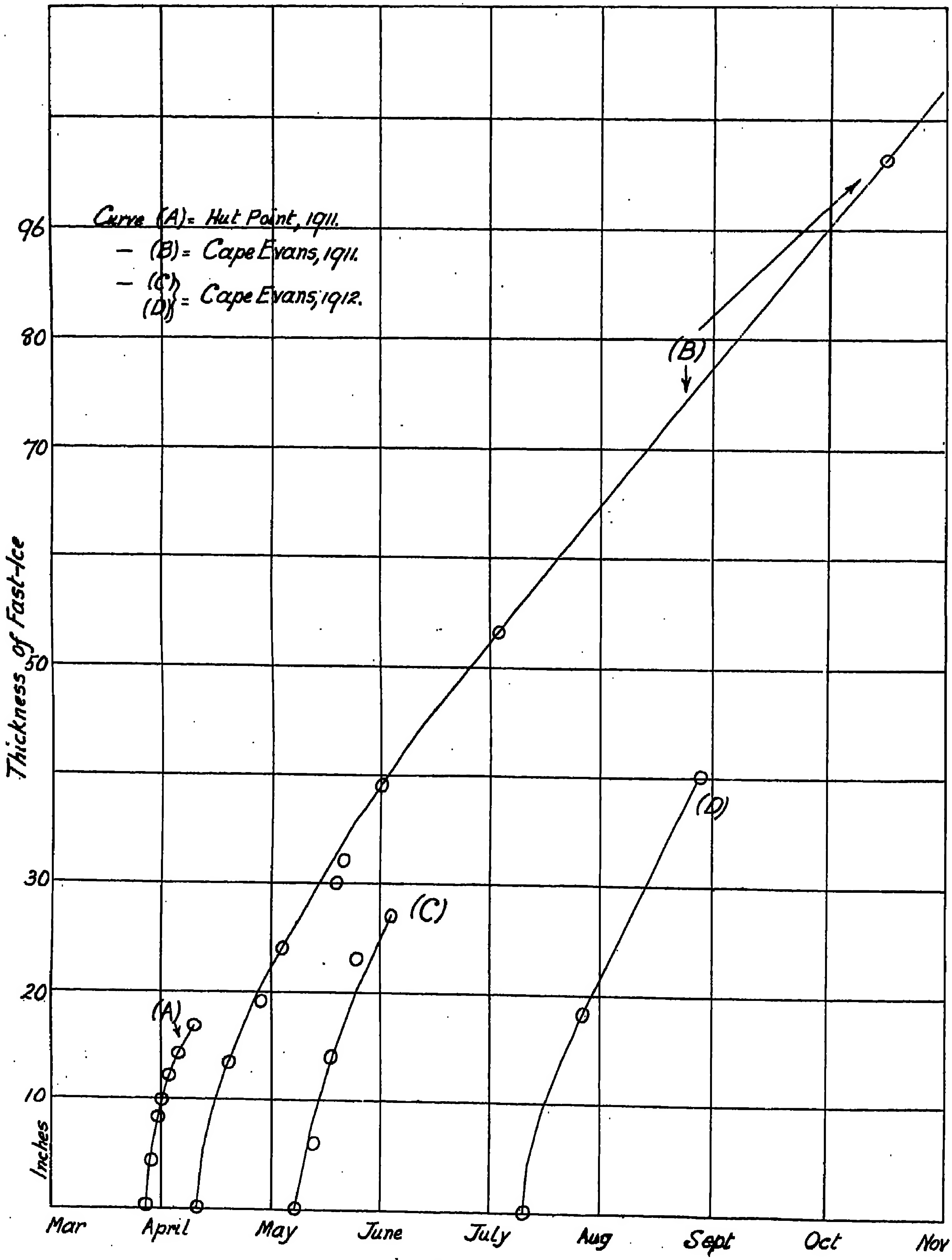

Curve (A) = Hut Point, 1911.
— (B) = Cape Evans, 1911.
— (C)
(D) = Cape Evans, 1912.
96
80
70
50
30
20
10
Inches
Thickness of Fast-Ice
(A)
(B)
(C)
(D)
Mar
April
May
June
July
Aug
Sept
Oct
Nov

Fig. 146.

arranged with their surfaces perpendicular to the surface of cooling. Except in the upper portion of the ice, these "fibres" are so loosely connected, that it is possible to pick the ice to pieces with the fingers, and it is difficult to prepare a section by sawing, since the ice crumbles so readily.

At Cape Royds, the headquarters of the Shackleton Expedition, this was the only type of growth observed in 1907–9; but there seems to be no doubt that in many places the ice owes a considerable portion of its thickness to the addition of frazil crystals.

The term "frazil" was originally applied to fine spicular crystals and ice plates which formed in the Canadian rivers, and which were prevented by the agitation of the water from cohering to build up a firm sheet. According to the description given of these crystals, the plates of ice which are carried by surface agitation and by currents well below the surface of the Antarctic Seas are of the same type. We have evidence that, in favourable positions, these frazil crystals rise to the under surface of the ice-sheet and sometimes form notable additions to its thickness. Growth by this means is particularly noticeable in the later months of the winter.

Attention was first drawn to these plate-like crystals at Cape Adare by their occurrence in the dredge when a haul was made. They had evidently been collected during the upward passage of the net through the water. When the "endless line" method of dredging is used in the Antarctic in sheltered bays near the winter quarters of the expeditions, a loop of rope remains suspended in the water sometimes for a considerable time, and it is to such lines that the frazil crystals attach themselves most readily (Plate LXVIII, Chapter III). On such a line, the individual plates may be two or more inches across. These plates are deposited in greatest number near the surface, and tail off very rapidly until they disappear completely at a depth of 3 or more fathoms.

There must usually be a considerable development of frazil ice where the sea is occupied by heavy pack, as at Cape Adare. The pronounced irregularities of the under surface of this ice must give rise to many quiet backwaters in which these crystals would accumulate and would subsequently become more or less firmly cemented (Fig. 147). This process must add in a considerable degree to the thickness and solidity of such pack areas.

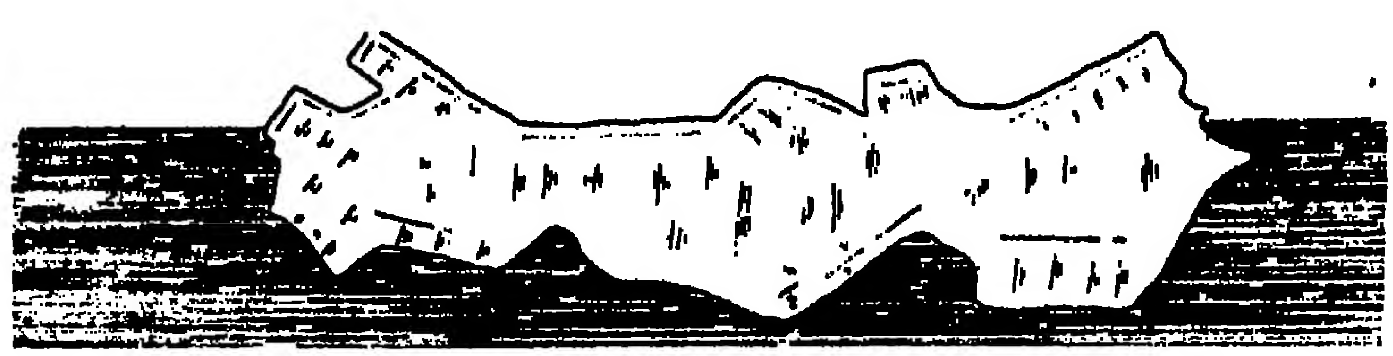


Fig. 147.—Diagram illustrating uneven lower surface of hummocky ice.

That such an accumulation of frazil crystals does take place was proved conclusively by a series of trenches dug in the sea ice of Robertson Bay, for the purpose of running a line of soundings. Whenever one of these holes was sunk through a very small flat pan amongst heavy pressure (as was usually the case), the bottom 2 or 3 feet of the ice invariably consisted of a loose mesh of such crystals. Only the top few inches consisted of what might be called "normal" sea ice. The probable cause of the accumulation of frazil crystals under these conditions is the protection against the current afforded

by the projecting portions of the thicker pressure floes. Whenever, on the contrary, a large flat pan was trenched, its lower portion was found to consist entirely of the "fibrous" ice already mentioned.

At Cape Adare, a beach of basalt pebbles slopes gradually beneath the sea, and for as much as 20 feet from the shore the submerged portion of this beach was partially covered, to a depth of a few inches, with a loose aggregate of Anchor-Ice which any slight disturbance would loosen and bring to the surface. They were then seen to be exactly comparable to the crystals which form the first indication of the freezing of the sea surface.

Locally, this Anchor-Ice formed a continuous sheet some square yards in area, but it was usually isolated in bulbous masses about a foot in greatest diameter. These were so full of tangled air that they looked like huge white puff-balls. When the crystals were dispersed, the air rose to the surface as streams of bubbles. Although a considerable portion of this Anchor-Ice must have been added to the frazil crystals floating on and in the water, most of it was probably absorbed into the tidal platform of the icefoot as that advanced seaward.

At Cape Evans, frazil crystals were not deposited on the manilla line used by Nelson in his zoological work until late in the winter, but in each season (1911 and 1912) their appearance and disappearance were well marked, crystals being deposited on the line almost every day after their first appearance.

The first record of their appearance in 1911 was on August 5, on which occasion the line had been in the water for 24 hours, and a slight deposit, varying from ½ inch at the top to nothing at 2 fathoms depth, was found. From this date onwards, crystals were nearly always deposited, whether the air temperature was high or low, and whether the sky was clear or overcast, the amount of the deposit gradually increasing as the season advanced.

On August 25, following a blizzard, a deposit of only ½ inch was recorded after 24 hours immersion in the water, this deposit being on *only one side* of the rope. Later still, as the surface ice thickened, it became evident that the deposit on the line commenced level with the under surface of the ice-sheet, where the maximum amount was deposited, the amount tailing off to nothing at a depth of 4 fathoms. The last record in 1911 was on October 22, after which date no frazil crystals were observed. A note in the diary states that Nelson, on this date, was of opinion that the type of plankton catch was different on October 23.

In 1912, the first record of Frazil-Ice was on August 28, the deposit gradually decreasing in amount until, at 5 fathoms, it disappeared.* As in the preceding year, frazil was recorded regularly after this date until September 26, which was the last date the crystals were seen, and then only in very small amount. A note in the diary suggests that the water temperature on this date was about 1/1000° C. higher than usual.†

* On September 18, the frazil crystals did not disappear until a depth of 9 fathoms.

† In 1911, the sea water temperature decreased gradually in South Bay, until a minimum was reached probably near the end of September. The rise in temperature during October was very slow—about ·01° C. in the month. A maximum salinity seems also to have been reached at the end of September, though equally high salinities were later observed in December.

Further light will, no doubt, be thrown on this phenomenon when the temperature and salinity observations and the tidal records have been reduced and the results are available.

It is worthy of note that, in 1911, the crystals appeared at an earlier date than in 1912 and persisted later, the presumption being that the sea temperature was higher in the latter year.

The previous remarks refer entirely to crystals deposited on a line sunk *below* the sea ice, and, before leaving this subject, it might be advisible to call attention to the particular occasion on which the crystals were deposited only upon one side of the line. Though this was only a single observation, it recalls the parallel case where frost crystals are deposited only upon the windward side of objects exposed to a slowly moving body of damp air. The conclusion reached in that case was, that the air contained small water or ice drops, even though these frost crystals were occasionally formed at temperatures below zero F.*

In addition to the frazil crystals formed under sea ice late in the winter at Cape Evans, a similar growth of crystals occurred on the sea bottom when no ice-covering was present, though it is, of course, possible that they were equally formed beneath an ice-covering, but invisible on this account. Crystals so formed appeared at an early date in shallow water, not only on the sea bottom, but also on various objects thrown into the water in order to ascertain whether the nature and colour of the object had any noticeable effect on the phenomenon. No selective deposition could be observed on such varying objects as a tin pail, a light coloured wooden box, or the dark rock forming the floor of the sea bottom. This suggests that radiation played no predominant part in causing the deposition, and indicates that the phenomenon is equally prevalent when there is an ice-covering. The formation of this Anchor-Ice did not appear to bear any relation to the cloudiness of the sky; for, though the records state that on March 29 masses of Anchor-Ice floated to the surface during cloudy weather, a note on the following day records that the masses had grown during the preceding 24 hours, though the sky had been cloudy almost the whole of this period.

In 1911, the first reliable record of Anchor-Ice is dated April 16, but Ponting reported that the phenomenon had been seen "about a month previously." In 1912, the first case recorded is on March 29.

Plate LXXI. is a photograph of Frazil-Ice deposited on a bucket. Plate LXVIII, Chapter III, shows Frazil-Ice on a dredging line. The latter had grown in 5 days, the mass being 6 inches in diameter, as shown in the photograph which was taken on September 18.

A thick coating of snow has a most distinct effect in retarding the growth of sea ice in the early stages, for it acts as a blanket, and largely prevents the exchange of heat between the mass of the ice and the water beneath it and the air above. This was

* *See* footnote on page 49. Our view is, that the sea water was actually supercooled and in equilibrium with tiny ice particles at this temperature, these particles being too small to act as nuclei for further deposition. *See also* 'Phil. Mag.,' January, 1922.

well seen in Robertson Bay during the spring of 1911. Here the whole of the ice east and west of the entrance of the bay was driven a mile or two to the north by the August gales. During September, an ice-sheet formed over the strait which had been opened. The temperature during the next month or two was certainly lower in the west of the bay, and the current there must have been considerably slacker than that sweeping round Cape Adare, so that the ice should have formed more quickly in the west than in the east. In spite of this, by October 8, the ice-sheet to the west of the bay was only from 9 to 12 inches thick, while that off Cape Adare to the east of the bay had reached a thickness of from 24 to 30 inches.

This is attributable to the fact that in the west, owing to the absence of wind, the snow had covered the new ice to a depth of over 2 feet, while the area round Cape Adare was kept clear of snow by the south-easterly gales.

It is certainly of interest to note, that the most favourable conditions for the transfer of heat from the water to the air are when no ice-covering exists; or, if there is an ice-sheet, no soft snow is lying on the ice. The meteorological conditions at Cape Evans, in 1912, were certainly most unfavourable, any ice which was formed to the north of Cape Evans being blown out to sea with the first violent blizzard. The cooling effect of the blizzard winds on the open sea in McMurdo Sound must, therefore, have been far greater in this than in the preceding year, when the Sound was covered with a thick layer of ice. The air temperature during blizzards is comparatively high, but the lack of an ice-covering to the sea must far outweigh this circumstance, so far as the cooling effect on the water is concerned; so that we may say with some certainty, that a sea bare of ice loses more heat than if it were ice-covered, in the circumstances under which each condition obtains in McMurdo Sound.

Due to this great loss of heat, the chance of the sea freezing over permanently (other things being equal) should increase as time goes on; and it was to us, at first, a matter of some surprise that the sea ice never retained a permanent hold on the shore north of Cape Evans in 1912.

From the fact that ice forms earlier in such situations as the bay between Glacier Tongue and Cape Evans than in the Hut Point area, it is clear that the circumstance favouring the formation of sea ice is largely the presence of obstructions (capes, islands, and even stranded icebergs) which prevent the ice from being driven north by the strong southerly winds.* In the absence of such obstructions, a long spell of cold, calm weather is almost a necessity, if the ice is to grow to such a thickness that it can resist the forces brought into play by a violent blizzard.

It is clear that the pressure gradient causing the strong southerly winds in McMurdo Sound is due to the large temperature difference between the Barrier and the Ross Sea, and, as Simpson has shown, any circumstance tending to increase the pressure

* The disappearance of part of Glacier Tongue early in 1911 may thus have a most pronounced effect on the date of freezing of the sea ice in this area. This effect may well have a practical bearing upon the fortunes of future expeditions to this district, as it is likely to be of sufficient magnitude to affect the average ice conditions in McMurdo Sound considerably.

gradient will operate so as to increase the wind velocity in the Cape Evans area. The occurrence of the air "pressure waves," which have been found by Simpson to affect the whole Antarctic continent, and even to be recognisable at Kerguelen Island, is, therefore, of considerable importance in fixing the date on which the sea ice will freeze in McMurdo Sound during any winter.

As the temperature difference between the Ross Sea and the Barrier is lowered by the freezing of the sea, the freezing of the sea tends to reduce the velocity of the southerly winds in McMurdo Sound.

The formation of a layer of ice also operates locally in another way by allowing the formation of a stagnant layer of cold air, over which winds of moderate velocity can pass without disturbing it. High winds, however, will sweep away the layer and remove the ice, so that the gradient wind extends down to the ground, thus increasing the mean wind velocity and mean temperature.*

Wind conditions and ice conditions are, therefore, in a state of unstable equilibrium, high winds causing conditions favourable for more winds; open water making conditions favourable for the continuance of this condition. A succession of days on which there are no high southerly winds is, therefore, a necessary condition for the formation of ice in McMurdo Sound; and the longer the period free from high southerly winds, the stronger the blizzard the ice-sheet so formed will be able to withstand.

A glance at Table LVII, 'Meteorology,' vol. 1, indicates the difference between the winters of 1911 and 1912, as regards high winds, calms, and mean temperature in the various months of these two years. The mean wind velocity, and percentage frequency of high winds and of calms, were almost the same in the two years for the month of March, the ice conditions during the month being very similar in both years. In April, 1912, however, the mean wind velocity and the percentage frequency of high winds were greater than in April 1911, while the frequency of calms was less. The difference between the two years was due to the calm weather in the last week of April, 1911. It was during this period, which was continued in the first eleven days of May, that ice of sufficient thickness to withstand the succeeding blizzards formed in McMurdo Sound.

From the end of April, the wind conditions in the corresponding winter months of 1911 and 1912 differed greatly, the mean wind velocity, the temperature and the percentage frequency of high winds being greater, while the percentage frequency of calms was less in 1912. We may consider the difference in conditions in the two winters as directly due, therefore, to the apparently fortuitous occurrence in 1911 of the long calm spell at the end of April and the beginning of May. It is of interest to note that neither June, July nor August of 1911 provided a calm spell of equal duration, though the conditions were, on the view outlined above, more favourable to their recurrence after the first formation of the ice-sheet.

A glance at the curves in vol. 2 of the Meteorological Report shows that, at the end of April and beginning of June, 1911, the pressure difference curve between Cape Evans

* 'British Antarctic Expedition, 1910–13—Meteorology,' vol. 1, p. 100.

and Framheim showed no very pronounced maxima. The conditions during this period were, in fact, unique. It does not seem unreasonable, therefore, to associate this formation of the ice-sheet in McMurdo Sound with the absence of pronounced air "pressure waves" (and blizzards) at the end of April and beginning of May, 1911.

We thus see that the relative amounts of ice driven north into the Ross Sea during the winter and following summer, which largely conditions the extent and distribution of the pack in the Ross Sea, may be dependent to a considerable extent on the occurrence or non-occurrence of a period free from the operation of air "pressure waves." The effect of the pack upon ocean currents must be far from negligible; and it seems possible that the simple occurrence or non-occurrence of a period free from "pressure waves" in the Antarctic in the early winter may exert a considerable influence upon climatic conditions at a subsequent date in regions far removed.

In the absence of any knowledge of the cause of these air "pressure waves," it is impossible to say whether or not the conditions in the Antarctic normally favour the occurrence of a spell free from pressure waves in the early part of the winter. It seems clear, however, that, in the absence of pressure waves, the conditions are less favourable to the occurrence of high winds the less the temperature difference between the Barrier and the sea. With open water conditions, this temperature difference is almost certainly greatest in the middle of winter, so that the chance of the occurrence of favourable conditions for the freezing of the Sound will (other things being equal) probably be less during the depth of winter than during April.

Judged by the date of first appearance of frazil beneath the ice, the water below was probably cooled to freezing-point at an earlier date in 1911, than in 1912. This would be a matter for surprise if McMurdo Sound were land-locked, as the exchange of heat between air and water must have been greater in 1912, when the sound remained ice-free, in spite of the higher air temperatures during that year. In view of the result actually recorded, one is forced to consider the possibility that the exchange of water between the Sound and the Ross Sea may be greater the higher the mean wind velocity in McMurdo Sound and the less the extent of surface covered by Fast-Ice.

Captain Scott has placed on record his view, that the temperature conditions during the return journey on the Barrier from the Pole were abnormally low and such as could not have been foreseen. The winter conditions which followed bear out this conclusion; and one feels that the unexpected advent of low temperatures on the Barrier, the great blizzard in which the party perished, the failure of McMurdo Sound to freeze in the autumn, and the unfavourable meteorological conditions at Cape Evans in the following winter, were all due to the same cause, viz., an early advent of a spell of low temperature on the Ross Barrier, which increased the temperature contrast against the Ross Sea.

(3) Growth of Sea Ice From Above.

Although the growth from below is normally the chief factor causing increase in thickness of the sea ice in the areas examined by the Scott Expedition, yet growth from above is not insignificant. Two types of such growth are particularly recognisable.

The first and most important (because more regional) is due to the accumulation of snow-drifts on the sea ice, and the subsequent change of their lower portions into ice, by the seeping of the sea water between the crystals of the sea ice as the accumulation of snow depresses the ice surface below sea level. Locally, the weight of snow may increase in one season to such an extent that considerable areas of the ice are flooded with sea water from the cracks which seam it.

A particularly good example of this was seen along the north coast of Victoria Land in the spring of 1911. Here the sea ice was covered with snow to a depth of several feet, and this overflow process had been responsible for an increase of at least 6 inches in the thickness of the ice. Under normal conditions along the coast of Victoria Land, the increase due to the saturation by sea water of the lower portion of the snow-drifts seldom, however, amounts to more than 1 or 2 inches.

The amount of any such increase will depend on the relative thickness of snow and ice and on the density of the snow. To take a concrete case, let us assume the densities of the ice and water to be 0·9 and 1·0 respectively, and the density of the snow to be 0·25. Free percolation of the sea water through the ice (neglecting capillary action) to the ice surface cannot take place until the upper surface of the ice is depressed below sea level. In these conditions, the sea water would also well up through any cracks which might be present in the ice.

If the sea ice is 10 inches thick, these conditions will be brought about by a fall of snow of the above density, totalling 4 inches in thickness. If the ice is 50 inches thick, 20 inches of snow of this density will be necessary to depress the ice sufficiently. It is clear, therefore, that this method of growth is most likely to take place, other things being equal, when the sea ice is still young.

As we have seen above, a thick layer of snow hinders the transfer of heat between the ice and the air above it, and notably decreases the growth from below. An area of sufficiently heavy snowfall, therefore, is one where the greater portion of the increase takes place from above.

It has been recorded by Drygalski* that, in the Pack-Ice off Kaiser Wilhelm Land, the greater portion of the growth of sea ice takes place in the manner just described.

His observations have since been confirmed by the experiences of the Imperial Transantarctic Expedition, 1914–17. J. M. Wordie has reported that in the Weddell Sea—the region traversed during the drift of the "Endurance" and the subsequent sledge and boat journeys—the accumulation of snow is particularly heavy, and that the growth of the sea ice from above is, therefore, very significant.†

From these and other similar observations, it would seem probable that in the main Antarctic "pack," where precipitation both in the form of snow and rime is higher than along the moisture-starved coasts of South Victoria Land, the sequence of events in the formation of the sea ice sheet is essentially different from that which has come under the notice of the British expeditions which have explored the latter coast. The sea ice thus

* *Loc. cit.*

† J. M. Wordie. 'The Natural History of Pack-Ice as observed in the Weddell Sea.' "Trans. Roy. Soc. Edin.," vol. 52, part iv (No. 31).

formed will have a radically different structure from that formed by growth from below, being more granular in texture and more full of included air. It will also frequently exhibit a horizontal lamination, the layers being often the result of individual snowstorms.

The second type of growth from above is due to a local flooding of the ice by water from tide-cracks, and the amount added to the sea ice in the immediate neighbourhood of the land is sometimes considerable. At times, the ice in a confined bay is under considerable compression, and cannot then adjust itself readily to tidal movements. The sea water then overflows the ice near the shore, and this process may continue, tide after tide. This process is probably responsible for the greater portion of the ice whose upper 1 or 2 feet show a very distinct horizontal lamination.*

The area affected is usually limited to a narrow strip between two parallel tide-cracks, the ice outside the second crack moving more freely than that in-shore; but on occasions this process has been observed to occur between as many as five different tide-cracks, the pools thus produced lying parallel to each other and to the coast.

This action, under favourable conditions, can be still more strikingly demonstrated, and a good instance of an extreme case was seen in the back of Robertson Bay, where the Dugdale Glacier was moving slowly forward and exerting strong pressure on the ice between itself and Duke of York Island. In this case, the edge of the original floe was depressed at least 4 feet below sea level, so that a total of 4 feet had been added to the surface of the ice in this way.

A certain thickness will also be added to the surface, especially in summer, by the normal change of the under surface of snow into ice.

Salinity of Sea Ice.

The salt-content of sea ice differs considerably from point to point, not only in a vertical, but also in a horizontal, plane, while evidence is given later to show that the salinity varies also in course of time.

This variability is not surprising, in view of the large number of factors which affect the growth and the crystalline structure of sea ice. For example, samples of sea ice from positions close to one another on the same horizon may differ considerably in their salt-content, according to the relative size and orientation of the ice crystals.

Determinations of the salinity of sea ice samples were occasionally made by titration with silver nitrate, the general results being given below :—

(i) The ice contains less salt than the sea from which it is formed. Other things being equal, the quicker the ice forms the greater is its salinity.

(ii) The greatest salt-content is found at the upper surface of the ice. The halide-content at the lower (growing) surface is also high, but less than that on the upper surface.

(iii) Except for the top 2 inches, the salinity-content is generally fairly uniform throughout any vertical section, varying in different samples from $\frac{1}{3}$ to $\frac{1}{2}$ the value at the upper surface.

* An exception to this statement is afforded by the case of laminated ice in which the layering is due to bubbles. In such cases, as will be shown in a different section of this memoir, an entirely different sequence of events has taken place. (Chapter XI, on "Pack-Ice.")

Attempts were made to get a quantitative measure for the rate of drainage of salt from sea ice suspended in the air, but there was no opportunity of carrying out this experiment, except in the low temperatures of the winter (May and June).

On the 20th May, a block of ice 12 inches deep was cut from the top portion of sea ice 32 inches in thickness. The salinity content was measured at different depths, and the block then suspended in the air with the original top surface up.

The variations in salinity observed are shown in the table below, the numbers being relative :—

—	May 20, 1911.	June 20.
Surface	22·75	11·23
4 inches below surface	6·5	7·85
8 inches below surface	6·5	7·6
12 inches below surface	6·43	—

The observed changes, at the air temperatures prevailing, were not large, the chief alteration in the month consisting in a redistribution of the salt-content.

It is, in fact, only when the temperature approaches freezing-point that wandering of the salt contents can take place to any very great extent.

It is of interest in this connection to note that, when a trench is dug in sea ice, even to very slight depths, the ice near the bottom of the trench, originally hard and brittle, becomes soft and slushy in the course of a few hours, due to percolation of brine through the ice. This shows that the ice, when close to freezing-point, is quite permeable to salt water. Under these temperature conditions, therefore, a salt solution will very quickly drain away from a block of sea ice.

Iceflowers.

When an ice sheet forms quickly at low temperatures, a considerable quantity of brine is caught up in the network of surface crystals. If the temperature remains low, the mother liquor becomes more concentrated as more and more of the water in the brine freezes, until finally the salt separates out as cryohydrate.

These specks of cryohydrate form small nuclei, on which the water vapour from the air deposits, building up beautiful fern-shaped or prism-like crystals, usually in groups of several individuals. These aggregates of crystals have been christened "Iceflowers," and are one of the most beautiful features of a fresh ice-sheet formed at low temperatures (Plate CCXXXI). Such iceflowers are akin to the frost crystals deposited under favourable conditions near all open water, but differ from them in the fact that they contain salt derived from the sea.

The most favourable conditions for their formation are afforded by the passage, at low temperaturers, of a body of air of relatively high humidity across a sheet of young sea ice. Under such conditions, iceflowers with crystals between 2 and 3 inches long have been observed to form in a single night.

Their most perfect development takes place in very cold calm weather, when the sea freezes over calmly and uniformly. In these conditions, the water vapour is evidently derived from the water entangled between the felt-like mass of crystals forming on the surface. The best development of this type of ice-flower was observed on a journey from Cape Evans to Butter Point in April, 1912. The weather was calm and the air temperature $-40°$ F. The thin sea ice for an area of some 50 square miles was found to be covered with masses of ice-flowers, the single fibrous spikes of which were sometimes 4 inches in length and $\frac{1}{8}$ inch thick.

When, however, the sea surface freezes under less calm conditions, the upper surface of the sea is often ridged as if formed originally from small pancakes whose edges were slightly upturned. Under such circumstances, the ice-flowers usually form on these small ridges, which are less warmed by the sea below and more cooled by the air above. Each ridge then appears to be outlined by a border of delicate white flowers. (Plate XXIX.)

Owing to the presence of salt in the crystals, the rise of temperature accompanying or preceding a strong wind results in the speedy dissolution of the ice-flowers, while the drift carried by the wind adheres to the moist surface of the ice and itself becomes saturated with brine. The snow so moistened usually then becomes a permanent addition to the sea ice, forming little ripples an inch or so high, whose appearance must be indelibly impressed on the mind of anyone who has ever travelled over sea ice, as they are very sticky and form the most difficult surface for sledges with wooden runners that it is possible to meet (Plate X).*

During the winter of 1911, waterholes opened at the entrance to Robertson Bay, and remained partially open for weeks at a time. On the new skin of ice which was formed round the outside of these holes, ice-flowers readily formed, but after two or three days their place was taken by lumps of ice often rather like inverted bulbs in shape, and attached to the sea ice by somewhat attenuated stalks. The only explanation which seems to account satisfactorily for this phenomenon is the constant super-saturation of the air over the waterhole, with a consequent extraordinarily quick deposition of moisture on the nuclei already formed by the coarsened ice-flowers. This saturation was proved by the pall of frost smoke which hung over the waterhole for several days after its formation. As in the case of the "foot stalactites," described under the heading "icicles" in another section of this memoir, the greatest development of these bulbs was towards the quarter from which the prevailing wind blew. The process seems to be analogous with that by which the "foot stalactites" are formed, with the difference that here the "frost smoke," moving gradually across the face of the ice with light northerly airs, takes the place of the drift carried by the southerly blizzards.

Above a temperature of $-7 \cdot 6°$ F., ice cannot remain in the solid state when mixed with sodium chloride in the presence of water vapour. This aspect of the question is of practical use in countries where the winter brings with it a succession of moderate

* Such a surface has become known under the name "salt-flecked" ice.

frosts. An example of its utilisation is afforded by the effect of sprinkling salt on pavements or on doorsteps which have been coated with ice. Its application to the question in hand is easily recognised, when it is remembered that sodium chloride is the only salt which exists in large quantity in sea water. If, therefore, it is a necessary condition of the existence of ice-flowers that they should contain common salt derived from the nuclei on which they originally form, we might expect to find that ice-flowers are unable to exist at air temperatures above $-7 \cdot 6°$ F., if the salt solution became distributed throughout the crystals in sufficient amount.

The figures given below in Table XIII show that this is not the case. There is no doubt, however, that small amounts of salt are generally present in the crystals, as is evidenced by their saline taste. This is the only definite evidence that salt cryohydrates form the nuclei on which growth takes place during the first formation of the ice-flowers. It seems probable that it is only at air temperatures above 0° F. that capillary forces enable sufficient brine to be drawn from the surface to cause the flowers to collapse.*

TABLE XIII.

The following Table gives the dates when ice flowers were noted in the Northern Party's ice log, and the corresponding uncorrected mean temperature for the day :—

Date.	Temperature.
	° F.
April 23, 24, 25	−3·5, −3·5, −2·5
May 2	+ 2·0
May 24	−16·0
May 26	−22·0
May 28	−20·5
May 29	−25·0
May 30	−21·0
June 1	− 4·5
June 22	−22·0
June 23	−26·1
August 23	−21·5

Interesting examples of ice-flowers forming elsewhere than on sea ice were afforded by the growth of small specimens on the surface of the new ice forming over trenches dug in brine lakes. There appeared to be a distinct connection between the degree of salinity of the brine and the number of ice-flowers formed on a given surface on the same or a similar day.

(*E*) *Pressure in Young Ice.*

For some time after freezing has commenced, the sheet of ice, as already mentioned, consists of a felt-like mass of crystals, which are only indifferently cemented together. If pressure is exerted on a portion of this mass, the cohesion is overcome, and each

* A single observation of the chloride-content of such ice-flowers at Cape Evans gave a value higher than that of sea water, and almost double the value obtained in the topmost layer of sea ice.

crystal acts more or less as an individual. The effect of this is excellently seen when an older floe is surging about in freshly-formed ice. In such a case, as many as a dozen concentric ridges may be observed in the young ice surrounding the floe (Fig. 148).

It is due to this lack of cohesion that young sea ice is unable to support the weight of a man until it has attained a thickness of 4 to 5 inches. Even this thickness of ice can hardly be considered to act as a rigid solid. This fact was strikingly borne out in short sledge journeys over young sea ice, the whole ice-sheet sagging under the sledge and party. The advance of a party over such young sea ice was preceded by an elevation of the ice corresponding to the depression caused by the weight of the party and sledge, or at least, there was every appearance of such an elevation preceding the party as it advanced.

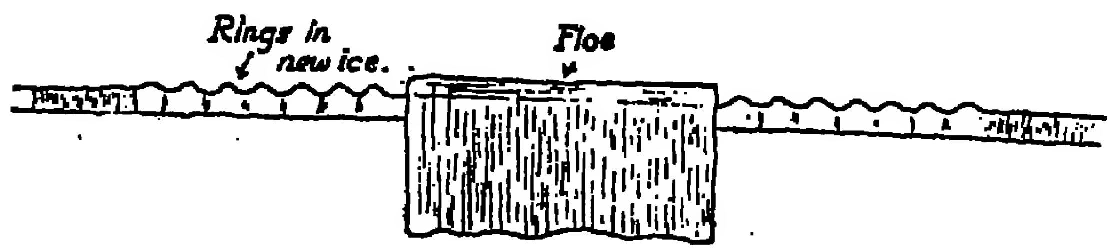


Fig. 148.—Pressure in young ice round a heavier floe.

Pressure blocks which have been formed when the ice is in this plastic state are marked by two characteristics :—

(1) Their edges are frequently rounded off and the scrapings scattered irregularly through the pressure ridge as amorphous masses of "brash" ice ; and
(2) The blocks themselves are frequently bent into a shallow arc (Fig. 149).

By long-continued steady pressure, blocks have been observed to have been bent almost into a semicircle, when still in the water at the time the bending took place. Directly the pieces have been raised above sea level, they commence to drain, and their plasticity, which is due to the brine between the ice-crystals, is quickly lost. This loss of plasticity is helped by the exposure of all the surfaces of the block to the cold air. After one of these curved blocks has remained out of water for a few hours, it will have become quite rigid, and can be shivered by a sharp blow with an ice-axe almost as easily as a block of fresh-water ice.


Fig. 149.—Young pressure formed at Cape Adare, 1911.

Another effect of steady pressure on young ice is seen in the formation of the so-called "drain-pipe" ice (Plate CCXXXII). This ice-formation is a direct consequence of the rise in temperature of an ice-sheet confined between two fixed boundaries, or between a line of stranded bergs and the shore. The ice is thrown gradually into a series of folds, which usually occur close to and parallel to the unyielding obstacle. The figured example (Fig. 150)

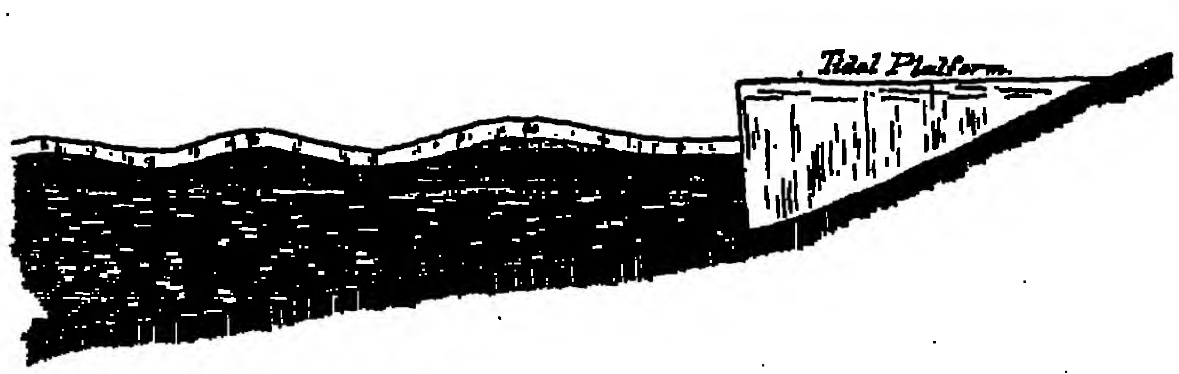


Fig. 150.—"Drain-pipe" ice at Cape Adare.

shows a treble fold of this type, which was one of the most striking seen, and was due to the expansion of a sheet of ice between the north shore of Ridley Beach and a line of bergs stranded on a shoal running parallel to the beach.

The process is best described in this place, since it is most typically developed in young ice, but it has also been observed to occur in ice several feet thick, when it is usually accompanied by fracture and overthrusting in the upper portion of the ice, which has lost much of its plasticity. The occurrence of slight folds in older ice is particularly well seen along the icefoot and before advancing glaciers. Excellent

Fig. 151.—Stages in pressure in young ice.

examples have been observed where the Ross Barrier advances against the sea ice in the bay south of Hut Point and in Robertson Bay, against the advancing face of the Dugdale Glacier.

Perhaps the best example of the effect of pressure on a plastic sheet of sea ice is observed when the ice is a few inches thick. If a steady pressure is slowly exerted by pack ice on an ice-sheet of this nature formed along an exposed coastline, the edge of the fresh-formed ice will slowly commence to uprear itself, and will slide over the seaward portion of the icefoot, nicely adjusting itself to all irregularities in the contours of the latter. The thin ice-sheet in this case behaves more like a very viscous liquid than a solid (Plate CCXXXIII).

The whole process of bending and breaking in young sea ice is well described in the following extract, which is taken from a diary kept at the time :—" A white patch like a frostbite appeared in the middle of the floe, and this spread until the whole floe showed

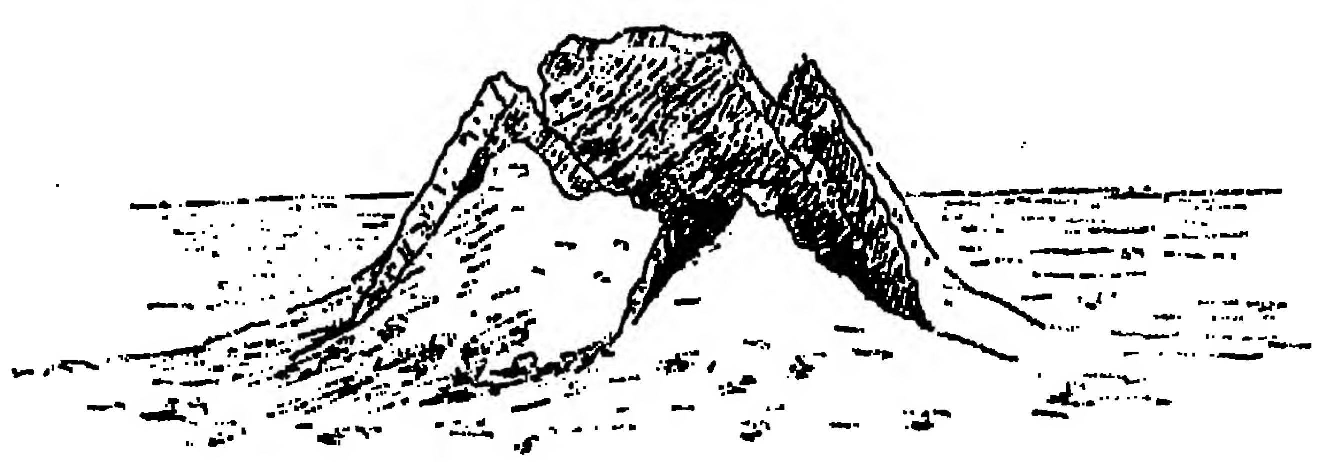


Fig. 152. (after a poor photograph).

white and opaque. The next stage was the bowing up of the floe into the form of a huge blister and then the edges began to crumble. This crumbling and breaking at the edges continued for some time, until the strain became sufficient to break the floe across the vertex of the arch. The two pieces formed when this finally took place were then telescoped and added to the ridge " (Fig. 151).

On several occasions, peculiar structures were observed in sea ice which resembled in appearance nothing so much as the skin of a blister, which had been broken at the top and the edges of which had curled back (Fig. 152). We have definite evidence of

the occurrence of gas bodies under the ice, and the only possible explanation of this type of structure is that it is due to such a gas body beneath the sea ice, causing an eruption through the plastic sheet in its successful effort to free itself. Once or twice, when trenches were being dug in sea ice, the first evidence of the approach to the bottom of the ice has been an escape of gas of sufficient violence to lift small fragments.*

(*F*) *Life-History of Fast-Ice before Melting.*

The ice-sheet which is formed in the manner described in the preceding sections of this chapter, if it survives the autumn and winter gales and persists throughout the winter, is modified by Temperature, Pressure, Wind, and Time; and it is now proposed to consider these modifications in detail.

(1) Modification by Temperature and Pressure.

These two influences, temperature and pressure, are intimately connected, and cannot well be considered separately, since one of the principal causes of pressure in Fast-Ice is change of temperature. The temperature range along the shores of the Antarctic Continent may not be excessive, but the changes take place extremely suddenly. During a prolonged calm spell, the thermometer may remain for days below $-35°$ F., while with the commencement of the gale, the ice may suddenly become exposed to a temperature from 50 to 60 degrees higher.

For instance, May, 1911, at Cape Adare, was characterised by one long period of calm weather, and one blizzard which lasted for ten days, with a period of varying weather in between. Such a rise of temperature, acting over a very large area, causes expansion in the ice-sheet, especially when the latter is thick. This, in its turn, sets up considerable pressure which is usually concentrated along shorelines, or against immovable objects such as islands and stranded bergs.

By this means, both shores of a bay, such as those on the eastern side of McMurdo Sound, where the ice conditions have been studied in some detail, show a succession of low troughs and ridges parallel to the shore. They are represented by long, low waves, usually with minute cracks across the vertices of the waves and the troughs between the waves† (Plate CCXXXIV). During the summer these cracks may play a pronounced part in the break up of the "Fast-Ice."

Other troughs and pressure ridges on a much larger scale, in which the sea ice has been broken up, are sometimes formed close to the shore. At Cape Adare it was possible to detect a new ridge and trough parallel to the southern icefoot of the beach after each of the three gales of long duration which marked the year 1911 (Plate CCXXXV).

* In some cases these gas bodies are undoubtedly associated with decomposing organisms. More usually they appear to be the result either of the trapping of air beneath the ice or of gases formerly dissolved in the sea water. From the sounds frequently heard beneath the ice, it seems probable that air bodies of the latter kind form valuable sources of breathing material to the Weddell seals.

† At Cape Evans, these waves run roughly parallel to the coastline. Within a bay, the more shoreward waves follow the indentations of the bay, the radius of curvature becoming less and less as the distance from the back of the bay increases. The waves are only a few inches high and one to two hundred feet apart.

Another effect of such temperature changes in a deep bay is the formation of heavy ridges of pressure ice against the inner side of all prominent points. This is due to the same cause as that which is responsible for the lateral troughs and ridges close to the coast, but is the expression of the expansion of the ice held between the points. The effects of this pressure are well seen from a glance at the accompanying map of Robertson Bay, which shows the position of the chief cracks and pressure ridges within the bay (Fig. 153).

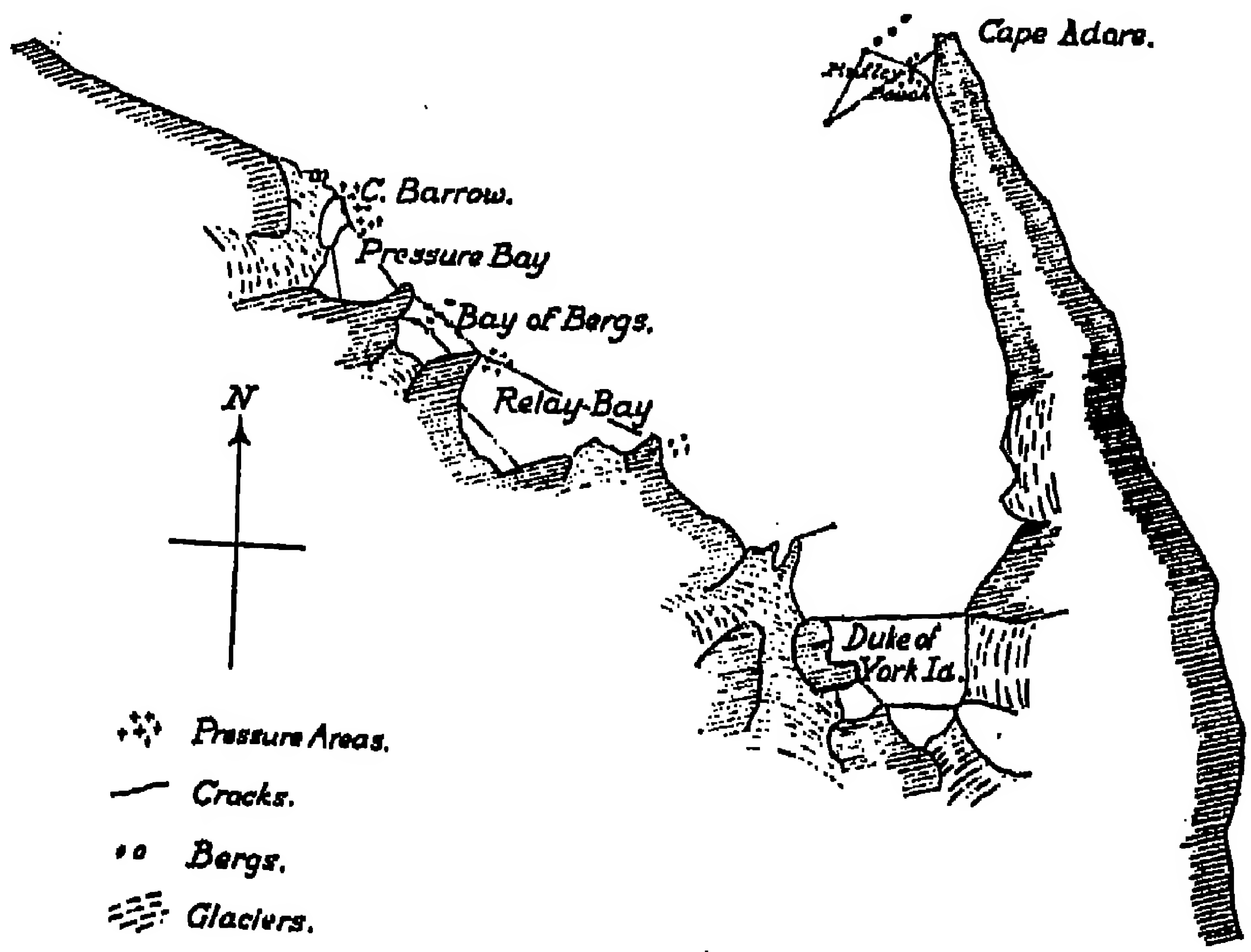


Fig. 153.—Map of Robertson Bay, showing the principal temperature cracks and ridges. It will be observed that they connect up the principal prominent points of the bay, or run between such points and stranded bergs. The pressure ridges are formed in miniature on the inner side of each of the points. These latter should not be confused with the much more prevalent and greater ridges which were due to the impact of the Ross Sea "pack" against the outer edge of the "fast" ice.

Another result of this same temperature change may be well seen anywhere in this portion of the Antarctic. When the first decided fall of temperature takes place towards the close of the autumn, a corresponding contraction occurs in the sheets of sea ice. Wherever fixed points, such as stranded bergs, prominent capes, &c., present an obstacle to this, contraction cracks appear in the ice. These usually run from one prominent point to another and their formation is accompanied by sharp reports.

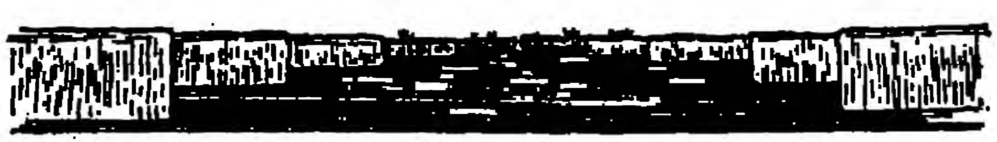
Those which formed in Robertson Bay in 1911 are shown together with the pressure ridges formed by rises of temperature in Fig. 153.

If the fall of temperature is great, the cracks are often of considerable width.* The sea surface exposed to the cold air gives off quantities of vapour and soon commences to freeze over. If the cold spell lasts for some time, the new sheet of ice may itself

* From certain measurements of the temperature of the sea ice, it appears that a change in air temperature of 50° involves a considerable change in the temperature at depths of 1 or 2 feet in thick bare ice, this change being naturally greater the greater the thickness of the ice. A change of only 10° C. is, however, of importance, as we see from consideration of the magnitudes involved. Taking the figure (·000028) given in Appendix I for the linear expansion of ice per 1° C., at a mean temperature of +8° F., it will be seen that a drop in temperature totalling 10° C. in a sheet of fixed ice 1000 yards long, demands a shrinkage of something less than 1 foot. It is only when we come to consider ice-sheets of large extent that we can expect the formation of large leads due to such a change. Thus, in McMurdo Sound, which is nearly 50 miles wide, one would expect a fall of temperature of 10° to be associated with the formation of leads totalling about 28 yards in width. This is of the order of magnitude observed, several leads about 20 feet wide having been observed on a sledge journey across the Sound from Winter Quarters to the Ferrar Glacier during the spring of 1911.

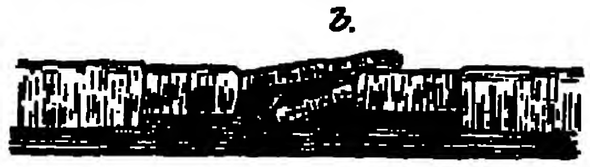
reach a considerable thickness, while further falls of temperature may tear it again and again. It is indeed a common thing to see such a crack with three or four strips of ice of different thicknesses bordering it. The fall of temperature is, however, frequently followed by an equally decisive rise of temperature, and then the old ice desires once more to expand to its former area. The new ice over the cracks is an obstacle, but a weak one, and it is at the expense of this that the adjustment takes place. The young ice in the "master-cracks" buckles, cracks and finally overrides as the sides of the old crack once more come together.

In this way a pressure ridge is formed, and remains as a monument to the cycle of temperature changes. The height of the ridge and the thickness of the blocks composing it are very nicely adjusted to the range of temperature change and the duration of the cold spell preceding it. Plate CCXXXVI shows an example of such a pressure ridge. Fig. 154 illustrates a compound crack formed in the manner described above.



Crack produced by a prolonged cold spell when the temperature dropped by stages.

b.



Overriding of young ice in such a temperature crack.
Fig. 154.

This process repeated again and again is the prime cause of the majority of the pressure ridges which seam the Fast-Ice of the bays, and which can usually be seen to run very definitely from fixed point to fixed point. As a rule, once such a ridge is formed, the crack which it conceals may safely be considered the line of weakness which will again yield at the next fall of temperature. Exceptions do, however, occur when new cracks are opened parallel to the older ones.*

(2) Pressure from Pack.

Quite a different type of pressure is produced by the movement of large masses of the "Pack" under the influence of wind, currents and tides. This type was best seen at the station under Cape Adare, which, being beyond the entrance to the Ross Sea, was exposed to the full force of the main Antarctic pack. The causes of the pressure set up in this area are probably threefold.

The effects of the westerly current and the tides are indubitable, but from the meteorological conditions accompanying the most striking examples, it seems probable

* It is interesting to note that these cracks are of distinct importance to the biologist of the shore party of an expedition wintering on the Antarctic Continent. There are many very good reasons for the selection of the shores of a bay for the winter quarters of an expedition. In such a position however, the sea ice remains in for a maximum period, and by its presence interferes very much with the work of the biologist who desires to dredge the sea bottom for animal life. In several expeditions practically all the hauls (and they have been quite numerous) which have been made during the winter and spring have been secured by the "endless rope" method. The cracks which have made this method possible have usually been produced in the manner described above.

that the onslaught of the pack was usually controlled and directed by a more southerly extension than usual of the "westerlies."

This conclusion was supported by the detection of a slight north-westerly swell, which could be observed on each of these three occasions, in spite of the damping influence of the ice. Further evidence was also afforded on similar occasions by the sighting of Antarctic petrels at Cape Adare, birds which should normally have confined their attentions at this time of the year to a region far to the north.

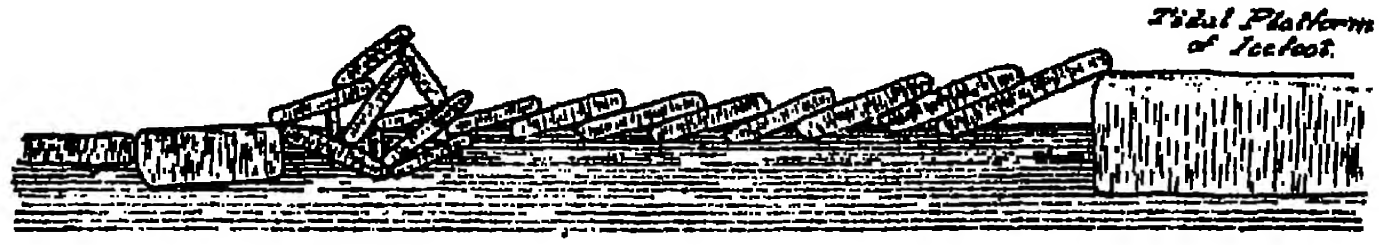


Fig. 155.—Ice-slate structure, Cape Adare.

The first effect of the pressure was noticed while the ice was still comparatively young, and the result was the type of pressure ice which the Northern Party named "ice slates" (Plate CCXXXVII; Fig. 155).

The ice-sheet in this case, as was usual at Cape Adare, was compacted of subangular pancakes, which had only recently been cemented together. In consequence of this the cement easily yielded, so that the individual pancakes were pushed over one another like the slates on a roof. At the same time, the softer lower portion of the pancakes was scraped from underneath the "slates," so that the resultant type of ice fully justified the name given to it. This type of ice was so common that it formed a characteristic feature of the surface for a distance of a mile or so south of the beach, though here and there areas of more confused pressure occurred.

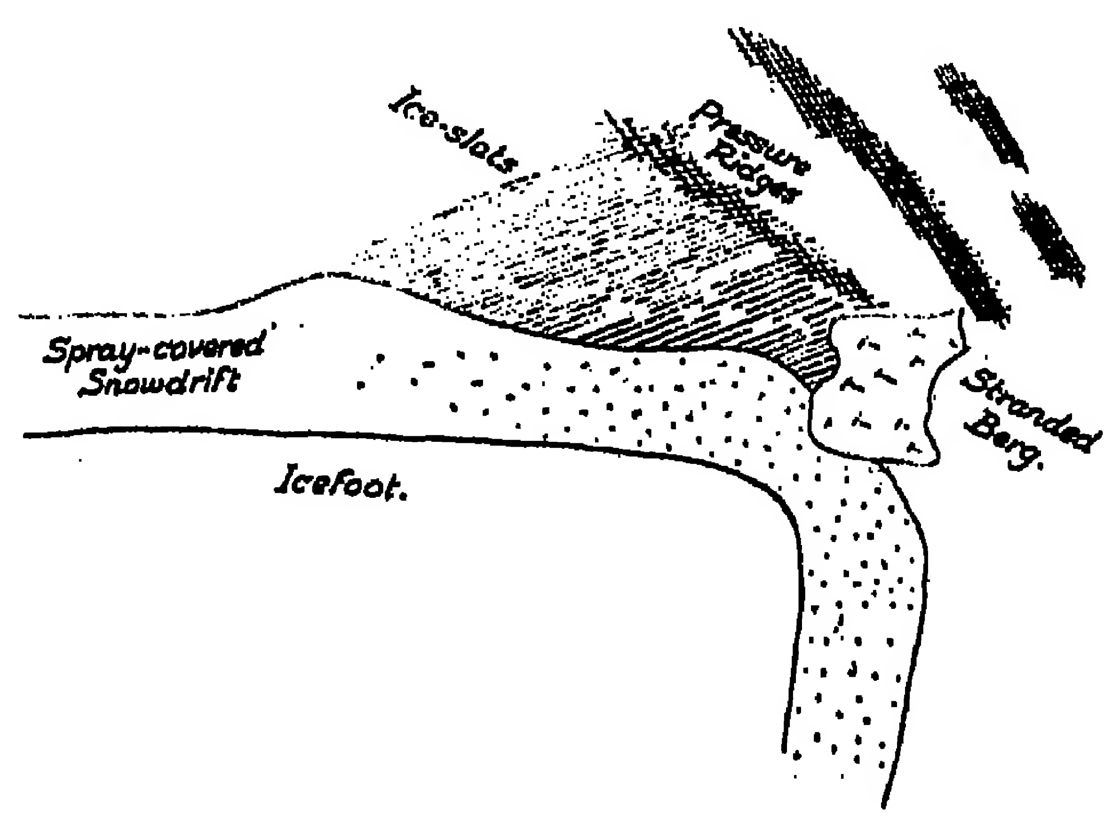


Fig. 156.—Plan showing two types of pressure described above.

Farther out into the bay, a wedge of pack had encountered somewhat younger and more plastic bay ice, and had driven itself into the latter, forming in it a series of little ridges of subangular pressure ice in the form of blunt-nosed inverted cones which resembled in shape the bow-wave of a ship. A stranded berg had diverted the pressure from the icefoot itself, and had caused the formation of two pressure ridges parallel with the shore but some distance out (Fig. 156).

For some time after the period of pressure which caused the results described above, the appearance of the pack was very intermittent, and the ice in the bay had time to reach a sufficient thickness to defy its assault before the next big onslaught was made.

On this occasion the ice crumbled at the edges, but otherwise stood fast, and most of the effects of the pressure were to be seen in the pack itself, where the heterogeneity of the component materials caused the crushing of the thinner floes and the formation of the "hummocky-floes" described elsewhere. The smaller pieces were frequently upended and pushed on top of the larger ones.

The Fast-Ice in the bay also diverted the pressure towards the east, and two or three parallel ridges formed along the northern shore of Ridley Beach near the Spit. These reached in places a dozen feet in height, though they never equalled the immense pressure ridges described by Borchgrevinck as occurring in 1899.*

The lower portion of the inner ridge was composed of small crushed fragments of the floes of sea ice 9 to 12 inches thick, which had been floating in an open lead off the north shore previous to the arrival of the pack. The upper portion of this ridge and the whole of the others were, however, composed of pack-ice varying from 2 to 4 feet in thickness. The pack-ice was easily distinguishable from the newer ice by its weather-beaten appearance and the fact that its lower portion was crowded with diatoms which gave a brownish-yellow tint to the ice. In every case, the slight dip of the beach prevented the pressure from reaching the icefoot itself.

Between the latter and the nearest ridge there was always a lane of level ice broken into small pieces, but held tightly together by the pressure from without.

Within the Fast-Ice itself, the pressure of the pack on this and on later occasions was responsible only for the formation of a few ridges and areas of younger pressure ice in regions where the current had retarded the growth of the ice and which were therefore areas of weakness.

In the beginning of May, all the sea-ice was driven out by a strong gale of long duration, and, after this date, the whole process of formation and modification was repeated. It is worthy of note that the stranded bergs persisted throughout this gale, and, when the ice formed again, the conditions just described were almost exactly duplicated. One would suppose from this that the process which has been just described is the normal sequence at Cape Adare.

Towards the end of May, the Fast-Ice in the bay once more became fairly firm, while the sea to the north was covered with a sheet of new ice a few inches thick. As the pack had been driven far to the north by the wind, this new ice at first remained level. Gradually, however, its edges commenced to crumble, and, all along the edge of the younger ice of the bay and along the beach, a ridge was formed which was composed exclusively of small blocks of ice less than a foot thick (Plates CCXXXVIII and CCXXXIX). For the next few days a continuous roar was heard to the north, as the pack advanced with irresistible force and wedged its way in towards the bay.

When movement finally ceased and the increasing frost had for a time conquered the pack, it was found to have reached within a mile of the beach. The ice to the north of this point proved, when examined later in the winter, to be chaotic. It consisted of a confusion of pressure ridges and areas, new ice mingled with old floes and small bergs.

* 'First on the Antarctic Continent.'

Even the previously level areas were uneven, for the ice formed the same year had been immediately converted into a brash of rounded and subangular pulped fragments, and these had been piled up until they were more difficult to traverse than the older pressure floes.

The ridges of the older ice frequently reached a height of 15 or 16 feet, and they were very numerous, crossing and recrossing in such an intricate manner that, in the hollows between the ridges, one's horizon was often limited to a few yards or even feet. This chaos of pressure ice undoubtedly played a leading part in the catastrophic breaks which will be described later and which were the most striking feature of the winter.

The effects of the tidal movements of the sea should not be lost sight of in this connection, though they play a more significant part during the break up of the ice. The flood tide in Robertson Bay accelerated the progress of the pack towards the new ice and added considerably to its destructive power, while the ebb tide tended to remove the pieces which had been broken up by the pressure during the flood. The tidal movements at Cape Adare were of course superimposed upon the constant current which swept past the cape on its way north along the coast of South Victoria Land.

(3) Effect of Glaciers.

The two agents already mentioned—temperature changes and pressure from the pack—certainly account for most of the irregularities to be noted in the surface of the sea ice; but one more agent remains to be considered.

All along the coast of South Victoria Land, glaciers push forward to the sea; and, although the movement of many of them is inconsiderable, yet that is not the case with all, and the mere presence of these long tongues of ice, extending sometimes many miles into the sea, has a most decided effect on the formation and subsequent life-history of the sea ice. Mention has already been made of the effects due to the advance of the Dugdale Glacier against Duke of York Island; but this case, although interesting, is of little significance compared with others which have come under the notice of the present Expedition. In fact, one of the best proofs of the stagnant nature of the glaciers about Cape Adare is afforded by the small effect which those on either side of Robertson Bay produce on the sea ice of that confined area.

It is now proposed to consider shortly the effect of three large Ice-Tongues on the sea ice adjacent to them. These three are:—

(1) The Drygalski Ice-Tongue, which is the seaward end of the David Glacier, near Mount Larsen.

(2) The Nordenskjöld Ice-Tongue, some 50 miles further south along the coast of South Victoria Land; and

(3) The Mackay Ice-Tongue in Granite Harbour.

The two former may be dealt with together, for both extend far out into the open sea beyond the narrow coastal belt in which the sea ice remains fast throughout the

winter. They have, so far as we have seen, no very great thrusting effect upon the sea ice around them.*

During the autumn, winter and spring of 1912, the Northern Party were detained at Inexpressible Island, to the north of the Drygalski Ice-Tongue. Throughout the whole of that time an almost uninterrupted series of north-westerly gales prevented the formation of sea ice of any thickness or persistence in Terra Nova Bay. The wind in itself, however, was not sufficient to account for the failure of the ice to form, and it seems that, in all probability, the ultimate cause was the presence of the great mass of ice to the south of the winter quarters. This must have deflected the upper and colder strata of the current sweeping up the western coast of the Ross Sea, and must have brought to the surface water from a greater depth, which was potentially warmer. This seems the more probable, since the ice showed a far greater tendency to form under the same meteorological conditions towards the end of the winter, when one would expect that these lower layers of the current would have been cooled to a considerable extent.

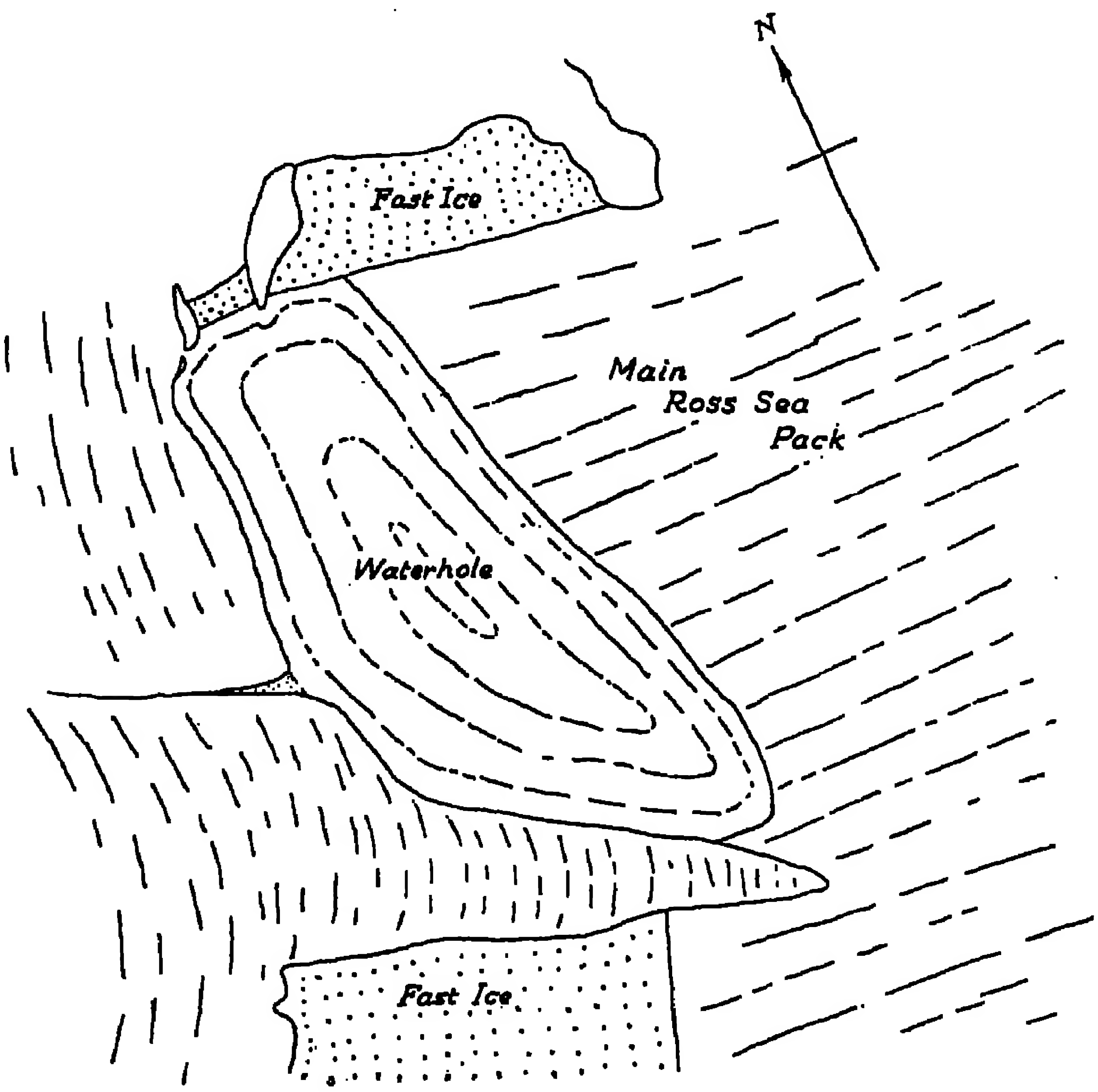


Fig. 157.—Sketch map showing approximate dimensions of the waterhole at Terra Nova Bay, in 1912.

The water-hole in Terra Nova Bay, which is shown in Fig. 157, extended along the northern side of the glacier as far as we could see. It is probable, judging by the extension of the "water sky" to the east, that the waterhole persisted to within a mile or two of the end of the Drygalski Tongue. At this distance off the coast, however, the main south-easterly circulation of the Ross Sea area might be expected to overcome the local westerly draught down the Reeves and the neighbouring glaciers. The boundary between the open waterhole and the Ross Sea pack would occur somewhere about this point.†

* Professor David, however, records the formation of wide cracks in the sea ice due to the advance of the Drygalski Ice-Tongue.

† It was bounded on the east by the pack ice of the Ross Sea and to the north by the Fast-Ice of the northern portion of the bay. It had a great significance from the point of view of the fortunes of the party, since, owing to its presence, it was necessary to traverse some 30 miles of unknown glacier before the Fast-Ice beyond the main tongue could be reached. The tongue itself was a known obstacle, since it had been crossed in 1908 by David, Mawson and Mackay.

The fact that thin sheets of ice did form from time to time during the calmer intervals of weather has an important bearing on the occurrence of ice in the Ross Sea during this winter.

As the Nordenskjöld Ice-Tongue was approached on the journey down the coast in October, 1912, conditions were met which are best explained by the postulation of a similar but less persistent waterhole in the lee of this tongue. Some ten miles before the tongue was reached the party encountered a belt of heavy pressure ice which, judging from its components, was chiefly old pack which had been circling in the Ross Sea during the autumn of the preceding year. To the south of this was a wide strip of ice extending right to the tongue itself, which was of considerably less thickness than normal one-year Level-Ice and which was probably formed late in the year, and after the northern portion of the waterhole had been filled with the trapped pack. In support of this view may be adduced the fact that this ice was very flat, and was therefore probably formed at a time when movements of ice on a large scale in the coastal region of the Ross Sea had almost ceased. This is precisely what would have occurred at Inexpressible Island had the winds been less violent. Fig. 158 is a sketch map showing the position of this "fossil" waterhole.*

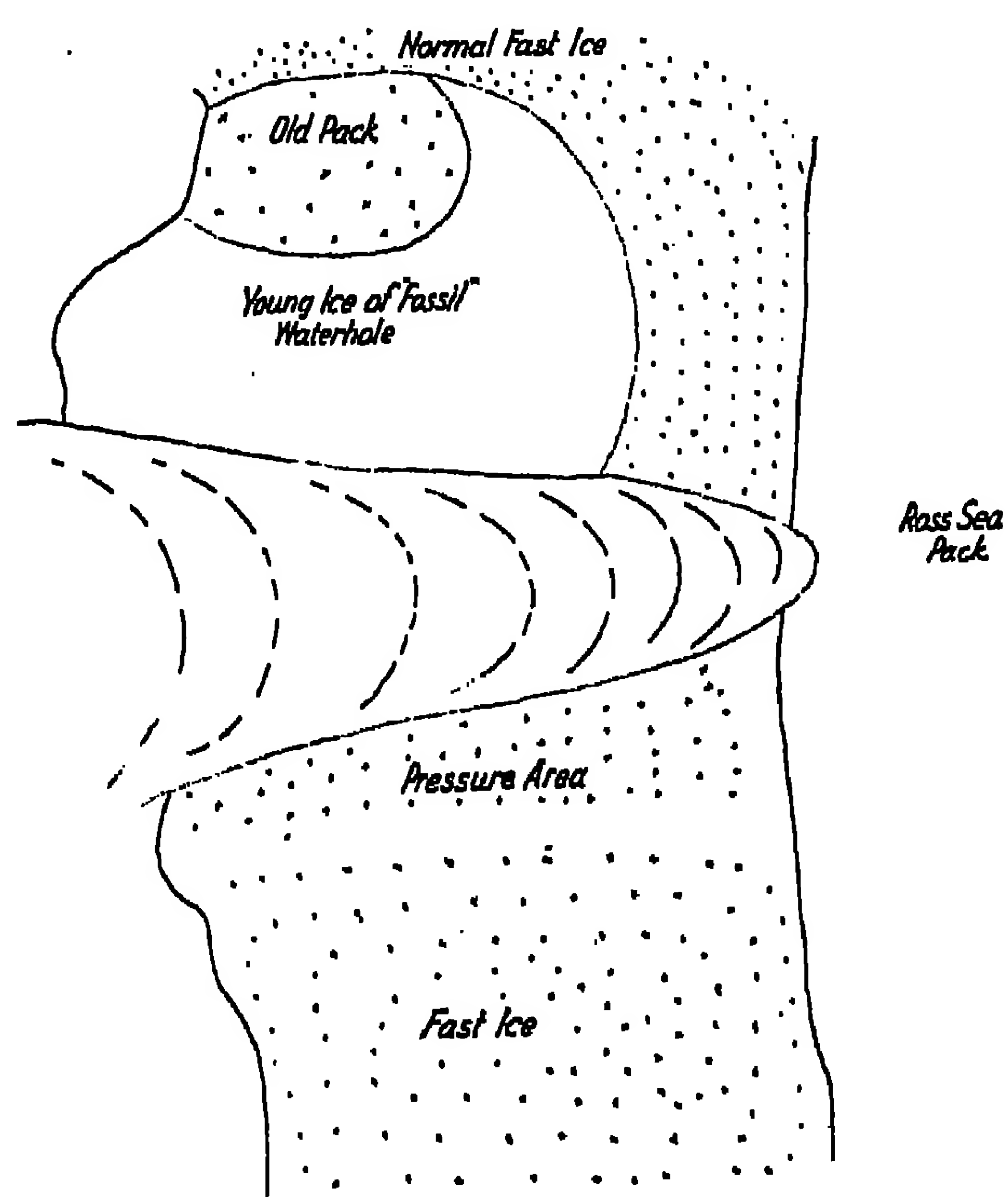


Fig. 158.—Sketch map showing position of the "fossil" waterhole off the Nordenskjöld Ice-Tongue.

The effect of these two tongues on the ice to the south of them is almost exactly what one would have expected in the case of similar capes of equal extent.

A certain amount of heavy pack had collected in the backwater formed at their base, and the same pressure effects due to temperature changes were to be seen, though in a slightly less pronounced degree than would have been the case between absolutely fixed points.

One feature peculiar to these free floating ice-tongues is the absence of any well-marked tide-crack. In fact, so uniform was the surface of the ice that the first open crack met on the march from the Drygalski Ice-Tongue southwards was well south of the Nordenskjöld Ice-Tongue. This was the crack across Tripp Bay.

* The drawing is very approximate only. At the time the waterhole was crossed, the Northern Party were on less than half-rations and in no case to stop and examine the coast closely.

The Mackay Ice-Tongue.

The influence exerted on the sea ice of Granite Harbour by the Mackay Ice-Tongue is entirely different from that exercised by the Drygalski or the Nordenskjöld. The two latter stand out as bars across the main current along an exposed coast. They extend well beyond the seaward boundary of the annual fringe of semi-permanent coastal Fast-Ice. The Mackay Ice-Tongue, on the other hand, occurs at the back of a deep confined bay, and its movement is considerable, a forward advance of 80 feet in one month having been measured by one of the Western Parties of the Expedition.

The secluded position of this ice-tongue debars it from exercising either of the main effects attributable to the Drygalski or the Nordenskjöld Tongue, but its forward movement is responsible for results which are even more interesting. In Fig. 159, which shows a portion of Granite Harbour in the immediate neighbourhood of the Mackay Ice-Tongue, these effects are illustrated.

Broadly speaking, four main effects of the forward movement of the glacier can be seen :—

(1) From prominent points on its face to the main projections of the coast, a series of "shear-cracks" extended, some of which were as much as 30 feet broad (Plate CCXL).

(2) The ice caught up between the advancing ice-tongue and these capes had been thrown into a series of folds similar to those already mentioned as occurring at Hut Point and in Robertson Bay, but on a much greater scale than the latter.

(3) Pressure was piled up on the inward side of all projections of the coast.

(4) The fourth and most interesting effect had been the gradual moving forward of the Fast-Ice of the bay, which represented the difference between the adjustment secured by the formation of the "shear-cracks," or by the crushing of the sea ice immediately abutting against the tongue, and the total adjustment required to compensate for the movement of the ice-tongue since the sea ice was formed.

This is an extremely interesting feature and was brought to the notice of the Party in an exceptionally interesting manner. To the south of the main tongue another little glacier advances into the sea in a direction slightly inclined towards the former. The differential movement of the two had caused a slight pressure ridge approximately parallel to the side wall of the tongue.

It was found that the ice blocks of which this pressure ridge was formed gradually decreased in thickness as the shore was approached, until the ridge died out at the icefoot in minute crinklings in one-day-old ice. A further investigation proved that, both here and on the outward side of all the projections of the coast of the bay, the sea ice gradually decreased in thickness in this manner, the decrease being a clear indication of the way in which the ice was being pushed bodily forward by the ice-tongue.

This is a very important fact, and may go far to explain why it is that the sea ice in many bays of the Antarctic shoreline is not more persistent. It would sometimes seem—as in the case of Granite Harbour itself—that, in spite of tide-cracks, wind and

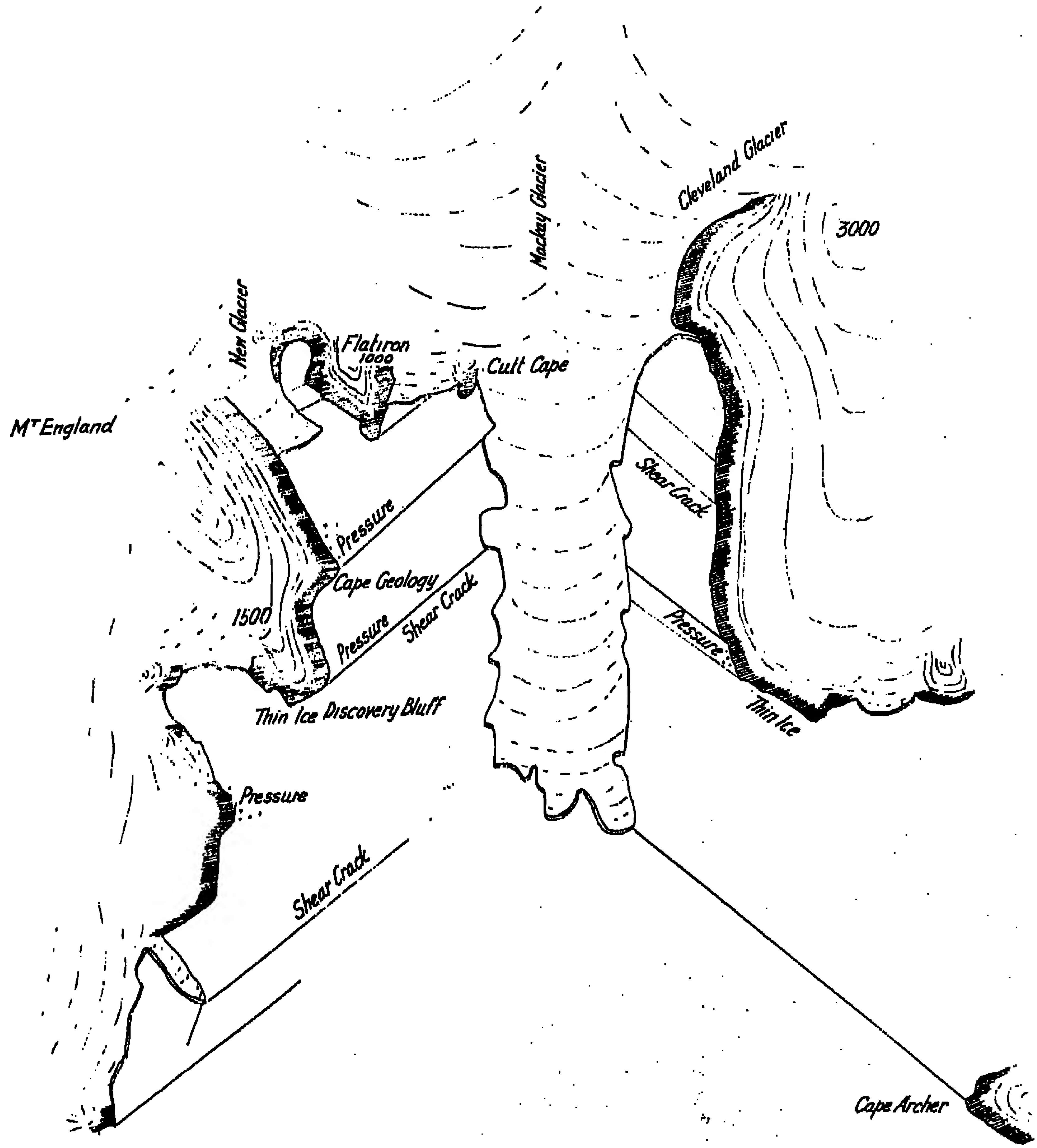


Fig. 159.—Granite Harbour, illustrating the effect of the forward movement of the Mackay Ice-Tongue upon the sea ice into which it moves.

swell, the sea ice ought as a rule to remain fast. In such a case as the one at present under consideration, and in the case of Glacier Tongue, we see a potent factor which will tend to prevent such a persistence, and thus to ensure that large masses of

Shelf-Ice built up in this manner are not likely to be common.* Most of the deeper bays of South Victoria Land have one or more such ice-tongues advancing into them from the glaciers behind, and the presence of such masses of moving "land-ice" is sufficient to ensure that the Fast-Ice shall be broken up and thrust out, except in a very exceptional season.

The cases of Fast-Ice persisting even for three or four years, which have come within the sphere of observation of the British expeditions to the Ross Sea area can be numbered on the fingers of one hand.

(4) Local Pressure Due to the Calving of Bergs.

Though the effect on sea ice of changes in the plane of flotation of icebergs is slight and is sporadic in occurrence, it is not entirely negligible. A good example was seen off a glacier in Relay Bay, one of the minor indentations of Robertson Bay. The berg, which stood between 50 and 60 feet out of the water, had been completely submerged after calving, and had risen and surged forward with such force that great damage had been caused, and the shattered blocks of sea ice had been thrust in great piles on to the fast sheet beyond the ice broken up by the calving of the berg.

Other blocks of sea ice had been lifted on top of the berg to anomalous positions 50 feet above sea level (Plate CCXLI). Blocks similarly perched on floating icebergs had previously puzzled observers until their mode of occurrence was made clear in this way.

This was not an isolated example, for perched blocks of sea ice were common on the numerous bergs in the Robertson Bay area, and were also seen occasionally in the pack.†

(5) Other Cracks in Sea Ice, and their Origin.

(*a*) *Tide-cracks.*—The cracks produced by changes of temperature have already been described and explained in the section headed "Pressure in Young Ice," but there still remain other types of cracks to be dealt with. By far the most common, and probably also the most important, of these, is the crack which borders all Antarctic coasts (except the faces of floating Shelf-Ice and Ice-Tongues) and which also surrounds all stranded bergs and islands.

These cracks are produced by the movement of the ice under the influence of the tide, and are known as "tide-cracks." It is due largely to them that the sea ice does not remain from year to year and, by the collection of snow upon its surface, form a considerable outward extension of the Antarctic Continent.

* The whole question of the formation of Shelf-Ice by the deposition of snow on the top of permanent sea ice sheets has been discussed in Chapters V and VI.

† Two other ways in which sea-ice blocks have been lifted on top of land ice 20 to 40 feet high have been observed in operation in the present Expedition. A heavy surf will throw blocks of sea ice of considerable size on top of land-ice cliffs fully 40 feet high, while, when a pressure ridge forms immediately against a berg or ice cliff, similar blocks have been seen to be lifted up some 20 feet.

A tide-crack along any shore may be single, but is commonly double, triple, or even fourfold. Along an open coast a single tide-crack is frequently found, but in confined bays, parallel cracks are the rule rather than the exception. These cracks closely follow the contour of the shore, and their number is usually increased by cracks across the mouth of any small cove.

Generally speaking, it was observed that the occurrence of a double, triple, or multiple crack was to be referred to the presence of a more or less gently sloping shore. The reason for this is easily understood, when it is considered that the working tide-crack is the line of fracture which permits the general ice surface to follow the rise and fall of the tide. This line is naturally formed as close as possible to the ice which is firmly fixed to, or rests upon, the land. On a shelving bench, therefore, the tide-crack formed with the first thin covering will be very close to the icefoot. As the ice increases in thickness, a time will come when the nearest portion of the floating ice-sheet will ground at low tide. Unless the sea ice is very thin, it will not be sufficiently plastic to accommodate itself to the altered conditions, and a second tide-crack, further out but roughly parallel to the first, will be formed. In a similar way, a third, fourth or fifth tide-crack may be formed, if the depth increases sufficiently gradually. The number of tide-cracks may therefore be dependent on the rate of increase of depth of water and the thickness of the ice. Usually, only the outermost tide-crack functions. This is therefore known as the " working " tide-crack.

The ice at the working tide-crack is never absolutely still, and a creaking sound is almost always to be heard. During the spring tides the movement is intensified, and the creaking rises to a whine as the sides of the ice-sheet attempt to adjust themselves to the new conditions, while their failure to do so is frequently marked by the overflow of large or small pools of water into the shallow, basin-shaped floes which line the shore between the tide-cracks.

At Robertson Bay, blizzards were always marked by increased movement at the tide-cracks, and, at times, the westerly swell from the Altantic beyond the girdle of pack would make itself most distinctly felt.

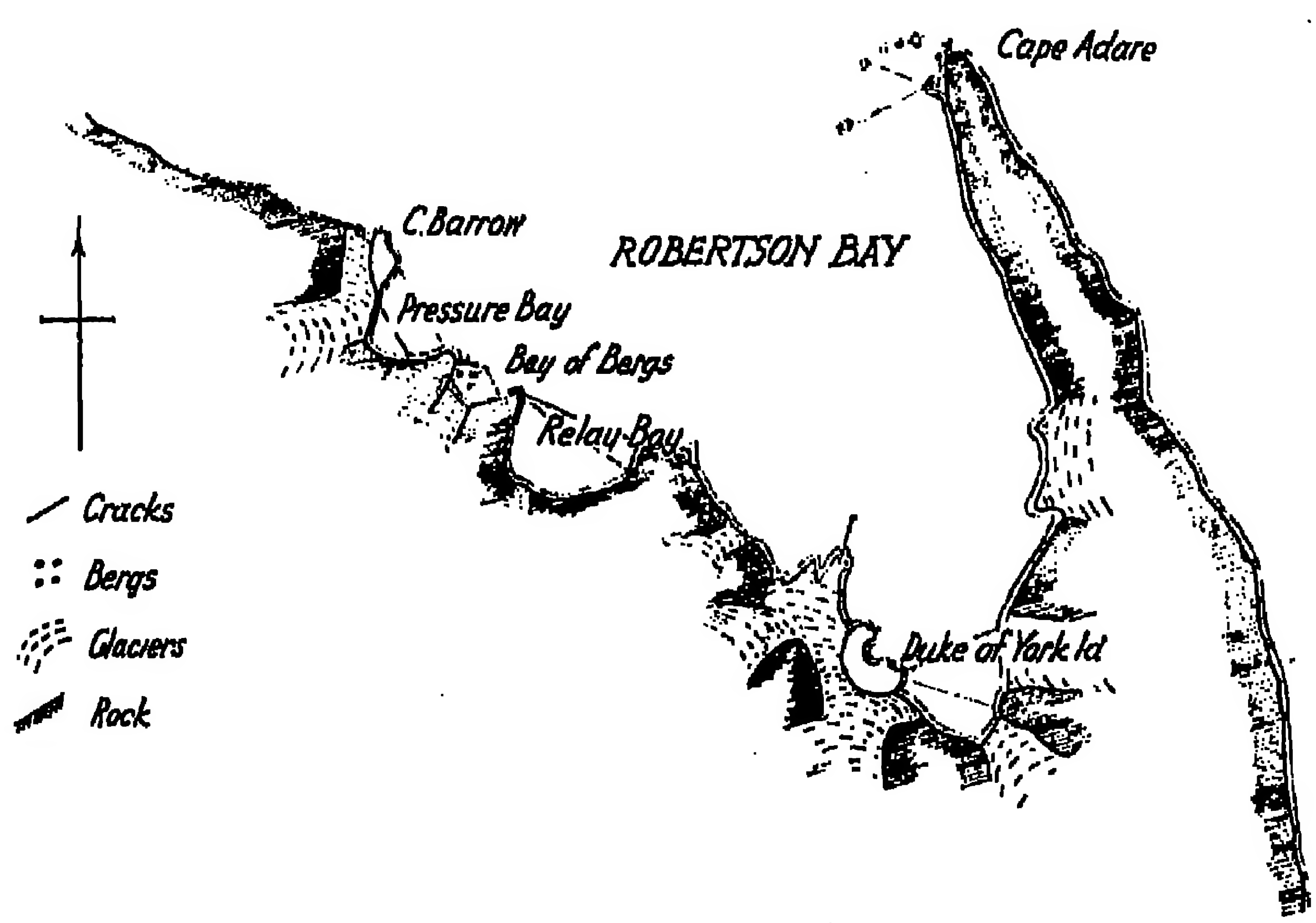


Fig. 160.—Sketch map of Robertson Bay, showing tide-cracks, the principal temperature-cracks, and the cracks across the mouths of the bays.

Fig. 160 is a sketch map of Robertson Bay, showing the principal tide-cracks.

(b) *Master-cracks across Bays and Coves.*—In addition to the tide-cracks which closely followed the contours of the coast, open master-cracks were always to be found at the entrance to the more pronounced bays. Good examples of these can be seen on the map showing the cracks in Robertson Bay where they cross the mouth of Relay Bay, of the Bay of Bergs, of Pressure Bay, and of Crescent Bay in Duke of York Island. These are opened and kept open by the differential expansion and contraction between the main ice-sheet which acts as a single mass, and the ice-sheets within the confines of the smaller bays, each of which also acts as a single smaller unit. The ice is thus torn apart at the entrance to each bay, and the changes of temperature keep this crack always open. The shearing nature of the effect was well seen in some of the cracks which, although straight lines, were very irregular, and were sometimes rendered discontinuous by slanting bridges left across them.

(6) Effect of Submerged Rocks on Fast-Ice.

The presence of a partially submerged rock is frequently emphasized by the occurrence of a local pressure ridge without apparent reason (Fig. 161.)

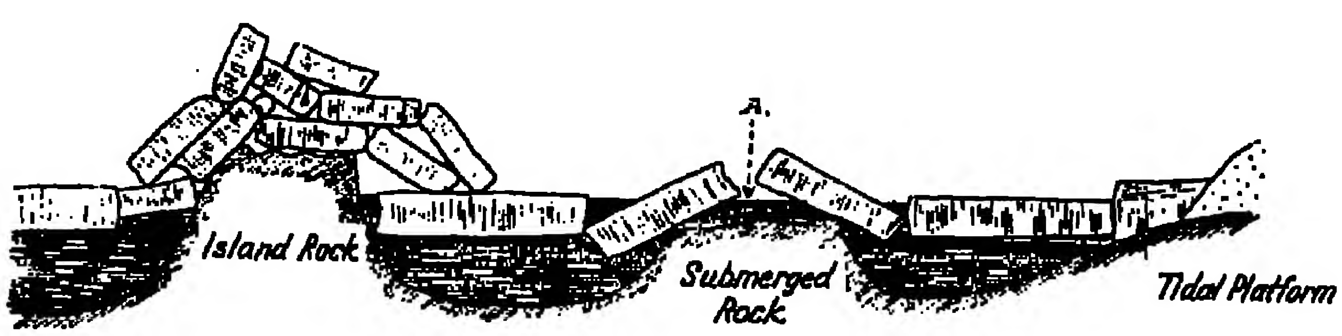


Fig. 161.—Local pressure ridge over submerged rock.

If the rock is completely submerged at high tide, but touches the sea ice at low tide, it forms a bulge in the surface ice, with cracks radiating from the apex in the form of a St. George's cross (A). These bulges and ridges are not uncommon along the coast near Cape Adare, where marine denudation has left many more or less prominent rocks isolated as outliers from the parent cliffs.

(7) Wandering of Salt and Effect on Ice.

The invariable effect of pressure, whenever and however it may be exerted, is to raise portions of the sea ice above the general level. Immediately this takes place, the brine in the sea ice commences to drain through the capillary spaces between the crystals. A cold spell may retard this process by freezing the brine completely, but, as soon as the temperature moderates, the brine again becomes liquid and, under the influence of gravity, moves further down towards the sea. The action continues vigorously until, finally, there is not enough salt left in the upper blocks of the ridge to be detected by tasting.

Attention was first drawn to this phenomenon when watering ship in the pack. As soon as progress was stopped by heavy Pack-Ice, the "Terra Nova" was moored alongside a heavy pressure floe, and the ridge was attacked by all hands and a great portion of it removed to the tanks of the ship.* Necessity probably had first caused the experiment to be made, and the result proved so successful that the possibility of obtaining fresh

* Watering ship from Hummocky Floes in the Pack is a practice which dates back before the days of Antarctic exploration.

water from what had been salt ice had been handed down from ship's captain to ship's captain.

The removal of the brine can become very perfect with time, and the whole of the water used for cooking and washing purposes at Cape Adare was drawn from huge floebergs* of pressure ice which had been stranded on the beach by the westerly swells in the previous autumn.

One result of this removal of salt from the ice is the loss of that plasticity which originally distinguishes sea ice from fresh-water ice, and this loss becomes so complete that a single blow from a pick will produce complex radiating fractures in a block which has been thus deprived of salt; whereas in freshly formed sea ice, a similar blow will only drive a hole into the ice and bury the point of the pick so that it is difficult to extricate it.

(8) Collection of Rock Material on Sea Ice.

During the winter, all the ice adjacent to rock-cliff shores becomes thickly strewn with rock fragments, and one of the most marked of the geological functions of sea ice must consist in the transportation of this material. This is fully treated in the Geological volumes of the Expedition memoirs. Much more important in the present connection is the sprinkling of fine dust and grit carried by the blizzard winds on to the areas of ice to leeward of any exposed rocks.

Both at Cape Adare and at Cape Evans, fragments half the size of a walnut were occasionally seen a full quarter of a mile from land, blown thither by the furious winter gales. The effect of these fragments in promoting the break-up of the ice is treated later in this Chapter.

(F) *Catastrophic Breaks at Cape Adare.*

No account of the life-history of the sea ice met during the present Expedition would be complete without some discussion of the "catastrophic" breaks which occurred from time to time in the immediate vicinity of Robertson Bay.

In some cases, these breaks were intimately connected with the local weather conditions, and of this type was that on May 6, when a hurricane removed all the ice from within sight.

The sea again froze over soon afterwards, and it seemed probable that it would remain for the winter, until another gale on June 20, which lasted less than 24 hours, but which was of great violence, formed a lane of open water which extended along the length of the northern side of the beach and was from one to two hundred yards in width.

After this lead was formed there was no further readjustment, and the open water froze over as an unbroken unridged sheet of Level-Ice. The local nature of the break suggests that the pack in the open sea north of the bay was by this time frozen together solidly enough to prevent any great movement of the ice through the agency of the

* Modified hummocky-floes.

southerly winds. It is probable, however, that a certain amount of latitude was still afforded by the screwing of the main pack and by the elimination of tracts which were too thin to resist the pressure set up, and were therefore crushed into pressure ridges occupying a smaller superficial area. This movement between the units of the pack, slight as it was, pointed to a lack of firm cohesion which we were later able to verify in connection with some of the later breaks.

On July 14, another lateral displacement, this time of a few feet only, took place; and this, as before, affected the ice north of the beach, producing a crack along the northern icefoot.

No local weather conditions could have given rise to this break, for there had been neither wind nor fall of temperature sufficient to account for it. It seems most probable, indeed, that it was caused by the thrust of the pack in the Ross Sea. Such an action on the part of the pack would be strictly analogous to the thrusting force exercised on the sea ice of Granite Harbour by the Mackay Ice-Tongue.

It was immediately after the break-up in June that columns of frost-smoke were noticed rising from the sea ice at a distance of 2 or 3 miles from the beach, and these became more numerous and larger at the time of the break of July 14. It was not until some days after this that it was possible to walk out and examine the nearer of these columns. It was then found that they indicated the site of open waterholes of varying size. The one nearest Cape Adare, which was examined in detail, proved to be only a few hundred yards in circumference.

No ice had formed over the centre of this patch, and the current could be seen racing past the ice which surrounded it. The hole had evidently once been greater in extent, but now ice had grown inwards from the west side of the break (towards which the current was flowing) until the original open space had been reduced to half its size. This ice dwindled in thickness as the open water was approached, as shown in Fig. 145.

As the result of the disturbance, the old sea ice was seamed with cracks, and a recent fall of temperature had caused these to open up, while the open water thus exposed gave off clouds of frost-smoke which rose in whirling columns. Further to the north, dense rolls of cumulus cloud bore witness to the occurrence of a similar phenomenon on a much larger scale.

The prompt appearance of Snowy Petrels and Antarctic Petrels at Cape Adare after each of the larger breaks during the winter, suggests that the ice to the north of the winter quarters was in a loose condition during the whole of the winter. It is unlikely that these birds would travel far over unbroken ice, since they require open water in order to enable them to obtain the crustacea and small fish upon which they feed.

The ice after this break never regained its stability, and the waterholes opened up from time to time apparently without regard to the local conditions (Fig. 162).*

During the autumn, winter, and spring of the following year (1912), the Northern Party were detained some 300 miles further down the coast. During their stay, as

* The direction of movement of the main pack in the Ross Sea is indicated, and also the region occupied by the Fast-Ice of the bay.

recorded elsewhere, ice never persisted opposite their winter quarters for more than a few days at a time, and the new ice formed during these short spells was soon broken up and driven north by the gales. Thus, in 1912, pack must have been moving constantly northwards in the Ross Sea and out into the South Atlantic Ocean. It is to the thrust of this pack that all such local breaks near Robertson Bay as were not directly connected with the blizzards there, must be attributed. Even those latter breaks doubtless owed their thoroughness in no small degree to the persistent "screwing" of the pack which prevented the individual floes from freezing firmly together. In effect, the ice beyond the confines of the bay was formed not of one single fast sheet, but of a breccia of angular pieces of ice moving in a more or less plastic cement of sodden slush.*

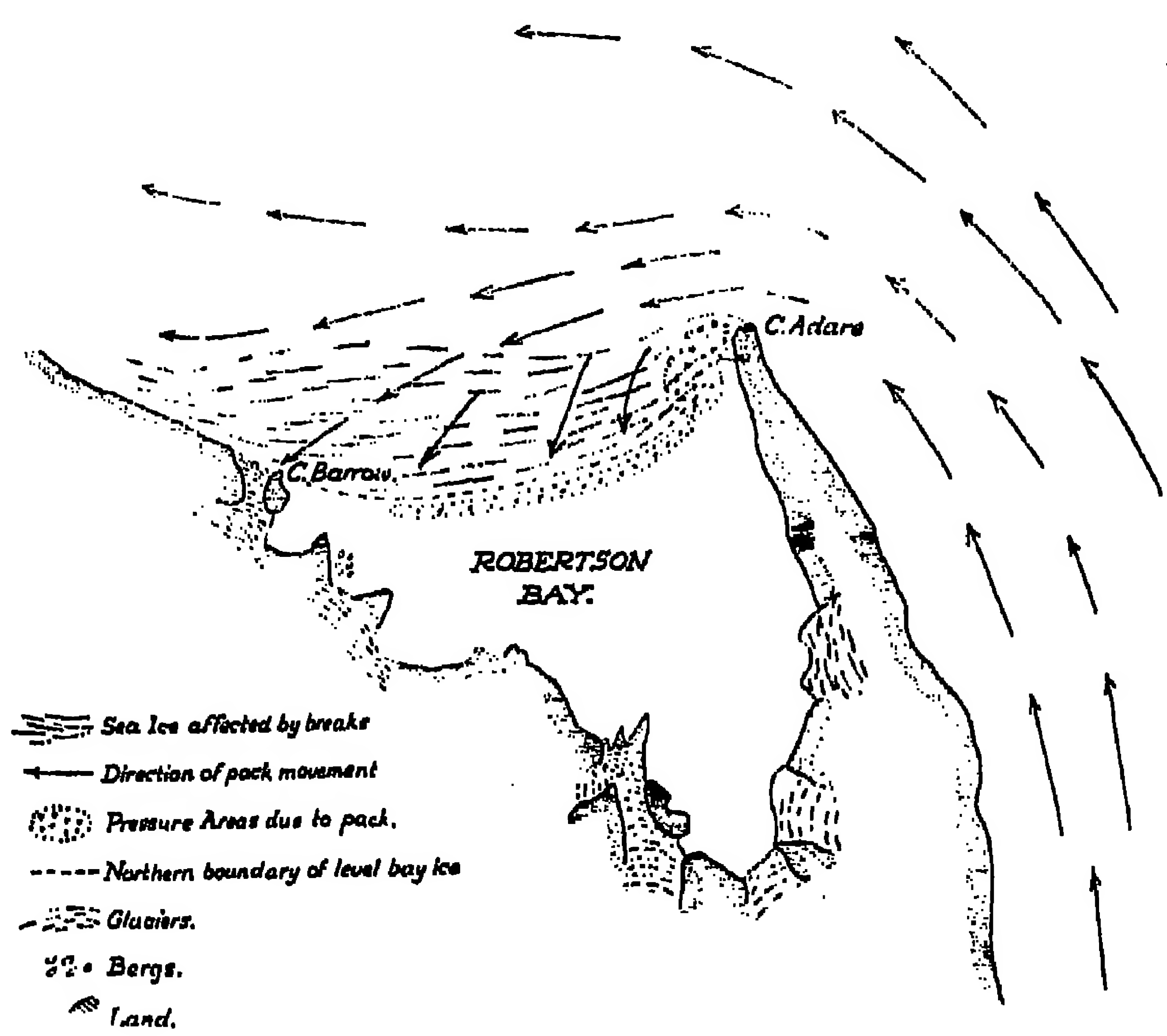


Fig. 102.—Sketch map of Cape Adare and Ridley Beach, to illustrate the section of the chapter on catastrophic breaks of the sea ice in this region.

August 12 saw the next great extension of the waterholes, when Campbell reported one between the beach and the "Sisters" (two isolated rocks to the north of Cape Adare), which was 400 yards long, between 40 yards and 1 foot in breadth, and connected with Cape Adare itself by a crack. Once again there had been no local weather conditions sufficient to account for the change, though the rupture of the ice might have been assisted by a fall of temperature of from 15 to 20 degrees which immediately preceded it.

It was on this occasion that a definite arrangement of the waterholes was first noticed, when it was observed that the larger ones had formed to the westward of bergs, of which latter there were many stranded off the cape. The smaller waterholes were generally to be referred to the presence of unusually heavy floes.

The former fact afforded definite evidence in favour of the theory that the waterholes were due to thrust from the east, while the latter was equally

* Since the date when these notes were written, the drift of the "Aurora" in the Ross Sea in the autumn and winter of 1915 has afforded a singularly complete proof of the instability of the main Ross Sea pack. The average speed with which this pack moved northward along the coast of Victoria Land in that year was over 6 miles per day.

decisive evidence of the greater effect of the current on the heavier units of the pack.*

A typical small waterhole off Cape Adare is shown in Plate CCXLII.

By the 14th, the waterholes had increased tremendously in size, until some of them might well have been described as leads; while to the west, north-west, north and north-east the sky became heavy with cumulus clouds and columns of frost-smoke, which showed that the disturbance was of a much more widespread nature than ever before. One lead extended right up to Cape Adare itself, and the sea ice had broken clean away from the near part of the end of the Cape as far as "The Sisters."

These rocks, and perhaps others less evident, had successfully protected the ice behind them from dispersion, but to the westward and to the eastward of this little patch the ice was all churned into small pieces.

The only lead accessible from the beach was the most southerly one, from which cracks extended in all directions out into the flat sea ice bordering the icefoot. At the south-west end of the open water spaces, signs of recent pressure were very evident, and the smaller blocks of ice had been thrust forward and upward from the north-east over the Fast-Ice. In some places to the south of the lead, a wall of brash, as much as 2 feet high, had been formed from rounded lumps of ice.

The ice-blocks of which the pressure was formed were only 24 to 30 inches thick, but they had evidently been a good deal thicker, their lower layer having been scraped off during the process of overriding.†

Near its western extremity, the lead decreased in breadth until it became a linear crack from which another crack ran abruptly to the north-west. West of this point there was no open water, but other evidences of pressure were soon noticed.

The ice between this point and the large berg stranded half a mile farther to the north consisted of small pieces of floe tilted in every direction, and the same agency which formed the waterhole had disintegrated this into its component parts. In every depression—that is, over about a third of the total area—were small pools of ice-slush, still soft, into which water welled when they were prodded with an ice-axe. Ice which had formerly been a corporate whole had thus been broken up until it was only a loosely-aggregated collection of *débris*, ready to be swept away by any power strong enough to overcome its inertia and such remnants of cohesion as were still present.

This power was provided a day or two afterwards when, on the 16th, a gale of unusual force even for Cape Adare, blew for 12 hours, and left behind it a legacy in the form of a strait, 2 miles wide opposite the beach and extending as far as the eye could reach to the westward.

Its limit could not be seen, even from the top of Cape Adare at a height of 1000 feet (Plate CCXLIII).

* The heavier hummocky-floes float deeper in the water, and their under-surface is irregular. They therefore present a much greater surface to the action of the current.

† Ice formed from Frazil-Ice, as was the lower portion of the floes north of Cape Adare, is very loose and easily disintegrated.

The thoroughness of the two agents—the thrust from the pack and the succeeding wind—was well demonstrated in the formation of this strait, the more especially because, to the north of the beach, there was situated a shoal on which was stranded a line of bergs, which it had been hoped would form a protection to the ice in their lee. These bergs had, however, proved to be agents of a far different kind, for, between them and from them to all prominent points of land, cracks had been formed as a result of changes of temperature; while, as has been pointed out, waterholes had been formed in their lee, due to their resisting the movement of the ice.

During a later sledge journey, it was ascertained that this particular "break" had extended right across the mouth of the bay for about 30 miles to the face of the glacier just south of Cape Scott. Even at its western end, it must have been of quite considerable width.*

The new ice which formed over this strait was again broken out and carried to the north on August 25, and this time, again, the cause of the break had to be sought beyond the range of conditions in the immediate neighbourhood.

A period of tranquillity now intervened and lasted for some time; in fact, there was no further disturbance of note until October 14, when the waterholes again opened up considerably. This proved to be the last recorded case of catastrophic break, and the future history of the ice was quite normal up to and through the final dispersion in the following December and January.

A comparison between the record embodied in the above remarks and that reported by the Southern Cross Expedition in 1899 is interesting, and would be more so if more detail could be obtained of the ice-conditions in the earlier year. So far as can be gathered from the official narrative of the 1899 Expedition, there was then no suggestion of any general break-up during the winter.† The first mention of open waterholes in the neighbourhood was on July 21, when Borchgrevinck, sledging round the *east* side of the cape, encountered bergs floating "either in a sheet of open water or in a bed of ground-up ice." West of the cape, which is the region dealt with in the preceding account, the first remark leading to any suggestion of loosening in the ice is dated October 27, when the writer says, "The ice pack seemed to begin to slacken at this date."

Bernacchi, the physicist of the 1899 Expedition, in a paper read before the Royal Geographical Society, is most emphatic about the possibility of examining the west coast as far as Cape North, an opportunity which he claims was thrown away by overcarefulness. This must mean that during the winter of 1899 the experience of the party was far different from that of the present Expedition.

It will appear later that there was no such difference between the dates of the final disappearance of the ice, so that these catastrophic breaks must be attributed to some factor or combination of factors which operated much more powerfully in the winter of 1911.

* Map XIII.
† C. F. Borchgrevinck, 'First on the Antarctic Continent.'

A comparison of the meteorological conditions at the station during these two years shows that they had many points of resemblance, and that the gales were somewhat more prevalent during 1899 than during 1911, though of about the same force.

It is necessary, therefore, to look for some other cause to account for the breaks, and it seems probable that the effect both of wind and current on the ice depends largely upon the position of the old heavy ice pack at the time of the freezing over of the bay and the sea immediately to the north of it. If the pack is far distant from the cape, so that a fairly uniform sheet of new ice is enabled to form inside it, then a stable ice-sheet will be formed.

Fig. 163.—Ideal section through a junction between level one-year-old ice and "hummocky" pack.

It is undoubtedly the irregularities in the upper and lower surfaces of the ice which give wind and current, respectively, a considerable portion of their power.

The relative hold given to wind and current by old "hummocky" pack and new level sea ice is well illustrated in Fig. 163, which is an ideal section through a junction between a sheet of such Level-Ice and an area of heavy pack.

The winds at Cape Adare probably lose their force rapidly as the distance from the cape increases, and the force of the current is greatly intensified round the end of the cape itself. If wind and current meet with very heterogeneous pack just at the spot where both can operate most powerfully, irruption of the pack against the Fast-Ice of the bay is inevitable. This is exactly what happened at Cape Adare in 1911. The sketch map, Fig. 164, shows the approximate position of the pack at the time the ice of the bay froze after the May gale. It can be seen that it was in position to do the maximum damage to the outer fringe of the bay ice, and to be itself torn away from the latter by the north-westerly thrust of wind and current.

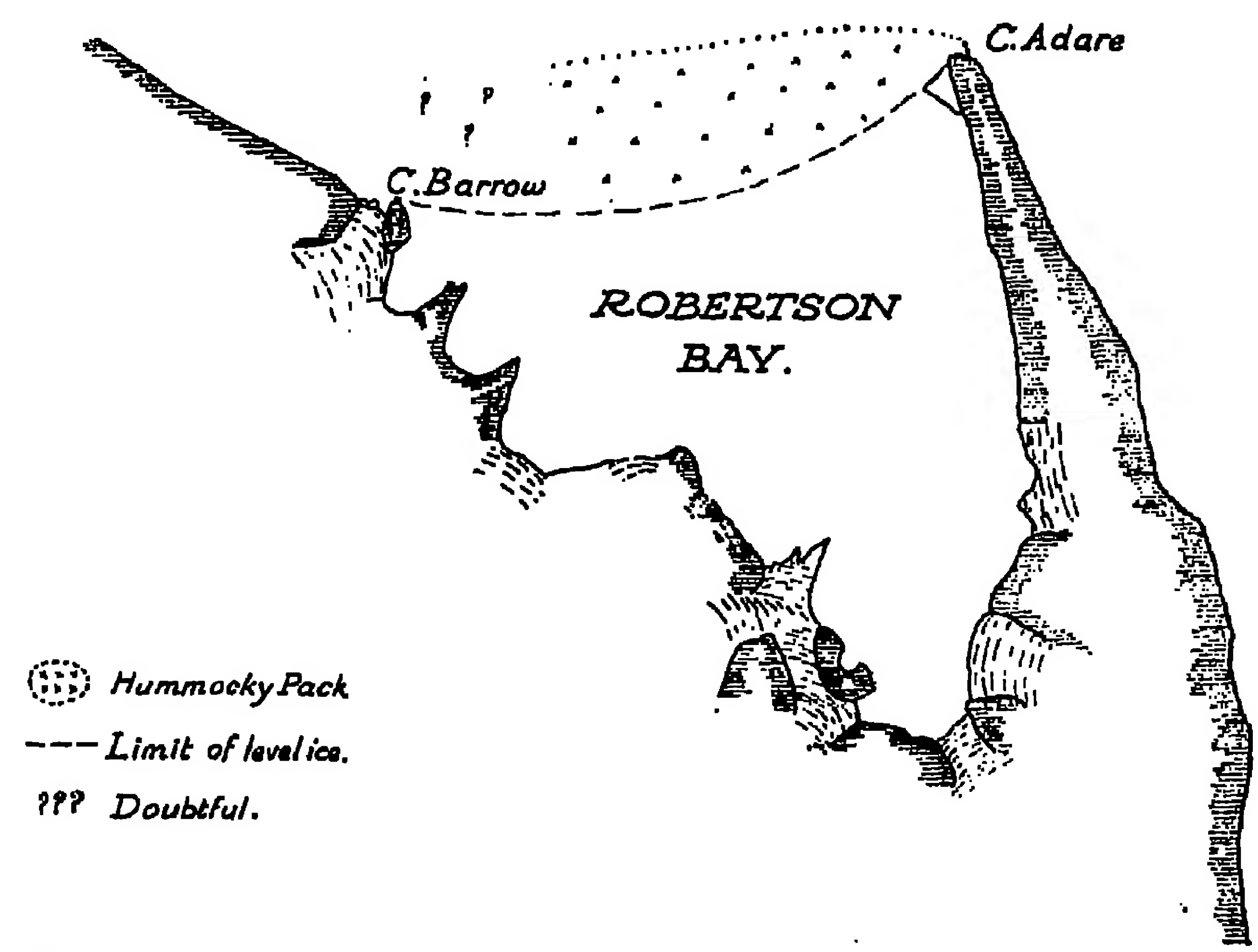


Fig. 164.—Sketch map of Cape Adare and Robertson Bay, showing the position of the Level-Ice of the bay, and the old "hummocky" pack ice in May, 1911.

It is only necessary to superimpose on these conditions a stormy winter along the shores of the Ross Sea, with a considerable consequent outward thrust of the Ross Sea pack, constant enough to prevent the ice outside Robertson Bay from properly

consolidating, and we have a combination of circumstances quite adequate to account for the instability of the ice in this winter.*

It is quite clear that the sea ice north of Robertson Bay is normally the transition zone between the Fast-Ice of the bay and the free-floating ice of the main Antarctic pack. In favourable years, this ice might remain fast throughout the winter and the spring. Such a state of affairs could, however, never be relied upon. At any time, heavy weather in the Ross Sea and the tangential thrust of the Ross Sea pack may cause an abrupt break of all the sea ice south of a shallow arc between Cape Adare and Cape Barrow (Fig. 164, pecked line; also Fig. 165).†

It will be seen from the sketch-map, Fig. 165, that Fast-Ice is of very insignificant amount compared with the extent of the pack. Elsewhere than in a comparatively enclosed sea, such as the Ross Sea, this discrepancy in amount will be still more marked.

This fringe of Fast-Ice, however, narrow and local as it is, has a very great importance to such Antarctic expeditions as endeavour to carry out the exploration of the coastline of the continent by means of sledge parties. It also affords the best opportunity for studying the growth of sea ice under ideal conditions.

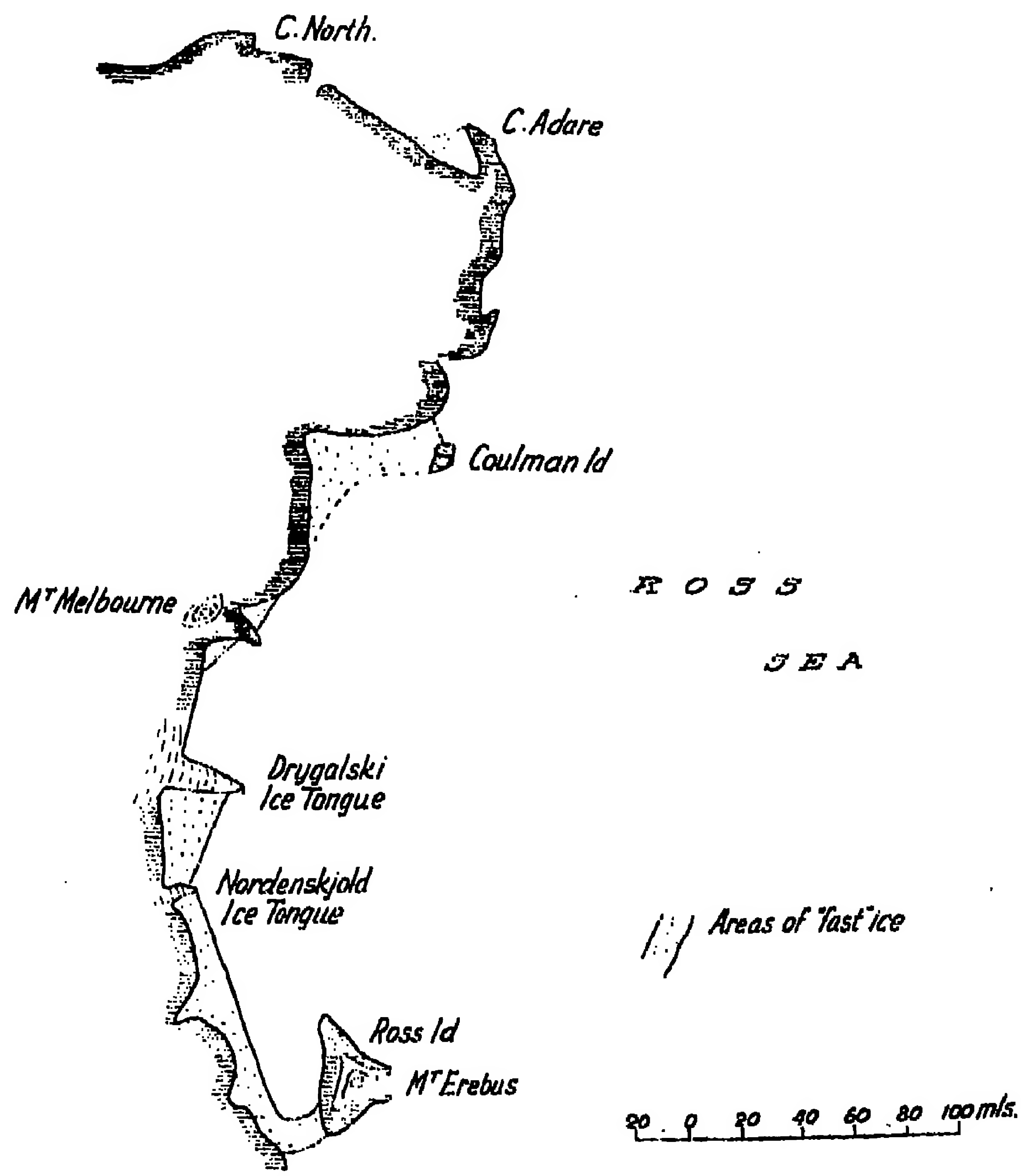


Fig. 165.—Sketch-map of the Ross Sea area, showing regions both known and inferred (the latter dotted) where Fast-Ice may be expected to form and last until the height of summer.

* The practical moral to be drawn from this comparison between the ice conditions during the two seasons at Cape Adare is of immense importance to Antarctic explorers, and may be summed up in a single sentence. Some type of boat, or some covering which can be used to convert sledges into boats, is an absolutely essential portion of the outfit of the Antarctic sledge party journeying over sea ice.

† A sketch-map of the Ross Sea area showing regions, both known and inferred (the latter in dotted lines) where fast-ice may be expected to form and last until the height of summer. (It will be noted that the principal known stretch is that stretching from McMurdo Sound to the Drygalski Ice-Tongue. Here there is normally a strip of Fast-Ice several miles broad, which affords a safe highway for sledging parties until the ice begins to rot and break up in the late summer.)

Finally, it is believed to give rise to occasional semi-permanent ice-formations of considerable extent and interest, though this is not true to any great extent in the Ross Sea itself. On all these counts it is worthy of close study, and this is the reason why the present chapter has been devoted to a somewhat detailed history of the evolution of Fast-Ice based upon the personal experience of members of the Expedition.

(*G*) *Disappearance of Fast-Ice.*

The last phase in the history of Fast-Ice is its disappearance and dispersion. Many factors play an important part in this, and these factors fall naturally into two divisions. These are :—

(1) Those which take effect before the final break-up commences ; and
(2) Those which directly cause this break-up.

(1) (*a*) *Ablation and Drift-chiselling.*—In point of time, the first factor to have any appreciable effect on the disappearance of sea ice is ablation. This consists in the direct change of ice into water vapour and its removal in the atmosphere, and is of course effective from the time of the first formation of the ice. It is seldom, however, that the ice-sheet remains free from snow for very long after its formation, and, before ablation can come into operation on the ice itself, this snow covering has to be removed.

In the removal of the snow, another process plays a very important part. Every gale which is accompanied by drift snow is armed with myriads of minute ice-chisels, and these cut the snow surface into ridges* and hollows, and may in the course of time remove it altogether. This drift-chiselling is a potent factor in the removal of sea ice, for, by its agency, large areas of ice may be laid bare to the full fury of the wind before the close of the winter. When the ice surface is finally exposed, the process of chiselling continues, though more slowly, and its depredations are added to the effects of direct ablation. In a district where drift is common, it is difficult to differentiate between the effects of the two agents and to estimate the amount of work accomplished by either of them ; but in a district where the winds are usually drift-free, as at Cape Adare and Inexpressible Island, a better idea can be obtained of the considerable amount of work carried out by ablation.

In the present chapter we are only concerned with the ablation of Fast-Ice, and attention will therefore be restricted to examples having reference to this. Elsewhere, however, examples of far greater weight are cited.

In the back of Terra Nova Bay, a sheet of Fast-Ice did form in April, 1912, under the partial protection of the Hell's Gate Piedmont, and this ice persisted for the winter. The wind was so incessant that the snow could obtain little hold upon this ice. As a result, after a couple of weeks, the latter had been swept and polished until it was far from easy to stand on it under any circumstances, and quite impossible in a gale.

In the autumn, a seal had been killed on this ice, and its blood, while warm, had melted its way in and had formed a pool which was not quite flush with the surface ;

* Sastrugi. For description, see Chapter I.

before the Party left the winter quarters the blood of this seal, although in a comparatively sheltered place, stood 2 or 3 inches above the general ice level. Such instances might be multiplied, but this example gives most conclusive evidence of the effects of ablation practically unaided by drift. It was very seldom that the winds blowing off Inexpressible Island carried any quantity of drift, though further to the north and south this was not the case.

A pretty proof of the effects of ablation plus drift-chiselling, and one frequently demonstrated over a large extent of ice, is to be seen where the sea ice was originally formed from pancake ice. When the snow is first removed, this pancake structure is frequently masked by an inch or two of ice, which has been formed from the lower layers of the snow which formerly covered it. As this latter ice is chiselled and ablated away white lines begin to appear which soon take on a regular arrangement, and are seen to be the churned-up edges of the former pancakes. If this process continues long enough, a perfect diagram of the initial structure of the ice is finally obtained. If the season is a windy one, this appearance may be removed in its turn by further ablation before the summer is far advanced.

Whether the weather is calm or stormy, ablation continues, save only when the atmosphere is saturated with water vapour. It is impossible, however, to pick out examples of this process without at once emphasising the very important fact that the amount of ablation depends to a most marked degree upon the presence or absence of wind. A gale of three days' duration will have as great, or a greater, effect than calm weather during a considerable period.*

One other example of the effect of ablation combined with drift-chiselling on Fast-Ice is worthy of record. On the Northern Party's first journey southward from Cape Adare, in July, 1911, the greatest difficulty was experienced in preserving the equilibrium of the sledge over an area of "spiky" pressure in young ice a few inches thick, which extended for a few miles to the south of the Cape. At the commencement of a spring journey in September, it was noticed that this pressure formed much less of an obstacle than had been expected from the former experience. The difference was at the time ascribed to imagination. By October, however, there could be no doubt that the pressure was much reduced in size, while many of the elevated pieces had had holes drilled through them and the ice was strewn with fragments of ice which had been broken off in the gusts of a recent gale. Half-way through November, before the summer sun had power to achieve any considerable melting, the pressure had ceased to exist as an obstacle, and an unusually heavy sledge was brought over it without any support being necessary.

All that was left of a very nasty pressure area was a few rounded knobs and low ridges of ice, with an occasional heavy floe bleonging to the previous year's pack which had been caught up in the new ice.

(b) *Effect of Grit and Dirt.*—On clean sea ice, little melting takes place until the height of the summer, and the only effect of the early summer sun consists in a slight

* As pointed out in Chapter VIII, this effect is nearly proportional to the square of the wind velocity.

glazing of projecting points of ice and a slight softening of the snow-drifts, so that these latter become " rotten " and give easily underfoot. In the lee of exposed land areas, however, where grit and sand are carried on to the ice by the frequent gales, the story is very different.

Within a few days of the first appearance of the sun, the larger pieces of the rock are seen to have sunk quite appreciably into the ice or superincumbent snow, while each individual grain of dust in the snow-drifts carries on its appointed work, and exercises a marked effect on the snow grains round it. The result is a gradual melting of the snow, or its removal as water vapour, and a consequent concentration of the dust on the surface of the sea ice.

It is not until the process has continued for some time that the observer realises what an immense amount of dust has been carried on to the ice by the winter and spring gales.

This process is to be well seen on the coast of McMurdo Sound, but it exercises a still more potent influence off the eastern shore of Robertson Bay. Here the rock is much more friable than the kenyte of Ross Island and the shores are much more abrupt. The amount of dust on the sea ice in 1911 was such that all snow had been removed from the ice by the middle of November, and the only suggestion of the former covering of snow was the regular arrangement of the dust as wavy lines over oval areas. These were very perfect " snow-drift ghosts "—pseudomorphs after the snow ripples in the hollows of which the dust was originally deposited.

As the summer reaches its height, the melting effect of the rock dust increases, and deep pits are scored in the ice which then becomes exceedingly treacherous.

(c) *Effect of the Temperature of the Air.*—Towards the middle of January, this melting begins to affect areas where the relative proportions of snow and dust are very different, and where the snow, although diminished in depth, has managed to survive.

Then, as the air temperature becomes higher, the ice begins to melt in earnest; and as the sea ice melts at a temperature below the melting-point of snow, the first melting commences and continues beneath the shelter of these persistent snow-drifts. At the same time, the sun evaporates water from the pools beneath the snow, and part of this may be deposited in the middle portion of the snow-drift, so that a crust of ice forms across it. This process may go so far that a snow-drift, formerly more than 1 foot in thickness, disappears, leaving only a thin ice-crust like a pane of glass. If the unwary traveller steps on this, the ice-crust breaks, and he steps into a pool of brackish water, which may be some 18 inches deep. Such an extreme case has not often been encountered, because the conditions necessary for its occurrence are not common in the Antarctic.

In a country starved of snow and subject to hurricanes, it is extremely unusual for any flat stretches of sea ice close to the coast to be deeply covered with snow; and it is also very seldom that the temperature is high enough, even in the summer, for melting to take place from above to any great extent.

(*d*) *Thaw Holes*.—Thaw holes are of two types, and both are the result of extremely local conditions. The best-known examples of thaw holes are those of Hut Point and Cape Armitage, which were first noticed and described during the "Discovery" Expedition, 1901–4, and which are due to the presence of shoals off these capes. The current sweeping past these capes is forced upwards by the shoals, so that, during the winter, one source of the growth in thickness of the ice, the collection of frazil crystals, is reduced, while the water itself, rising abruptly from greater depths, is at a higher temperature than that near sea level at other points in the Sound.

It is therefore certain that, at the beginning of summer, the ice off these points is less thick than elsewhere in the Sound. Immediately the temperature of the water rises, and it commences to melt the lower surface of the ice, the removal of the ice proceeds much more rapidly over these shoals, where the current is probably swifter, and where the lower layers of water are deflected upwards. Plate CCXLIV shows such a waterhole off the Barne Glacier.

The result is that, long before any visible effect is produced in any other part of the bay, the ice becomes rotten over these shoals. At first, the snow covering may give little indication of the insecurity of the ice below, and, in this condition, the ice is most dangerous to travellers. Later, however, a black patch of open water appears over the centre of the shoal, which spreads rapidly until the ice in the middle is entirely removed and an open waterhole surrounded by very treacherous ice is formed. A single day is often sufficient to render thick ice unsafe for travel.

A similar deficiency in thickness was noticed over the shoal north of Cape Adare and it was here that open water first appeared in the summer.

The second type of thaw-hole is formed by radiation from masses of black rock, and here again the best examples are found in McMurdo Sound. The Dellbridge Islands are formed of masses of dark volcanic rock rising sharply from the sea bottom about half-way down the Sound. The effect of the summer sun on these rocks is to raise their temperature considerably so that they radiate heat to the air and the ice around them. This constant radiation has considerable effect on the sea ice near them, as, indeed, in the case of the largest of the islands, may be gathered from its name (Inaccessible Island). The islands are thus surrounded in early summer, sometimes for two or three months before the final break up of the ice, with these "radiation" thaw-holes, which increase in size as the summer advances.*

(*e*) *Effect of Temperature of Water*.—The pack near Cape Adare generally loosens to a great extent during October and November, leaving large patches of open water exposed to the rays of the sun, and thus the whole body of surface water is warmed during the course of the summer.

* The equivalent of the "radiation" thaw-hole in the Antarctic glacier is the "radiation" gully which borders portions of the glaciers. It is probably largely because of these holes that Weddell seals, which must have free access to the water, congregate on the ice round these islands in the breeding season.

It is some time before the rise of temperature makes itself felt to any great extent, but, towards the close of January, unless the effect is forestalled by the break up of the ice through the catastrophic action of wind or pack, the seaward portion begins to melt quickly from beneath and is then easily scattered. A good example of this " rotting " caused the loss of a motor sledge during the landing of the main party's stores at Cape Evans.

The " Terra Nova " had been moored to the bay ice for some two or three days, and heavy sledges loaded with stores had been constantly going to and from the ship. Captain Scott had noticed the weakness of the ice, and orders were given on January 8 to disembark the remaining motor sledge at once, and haul it ashore before the ice became too rotten. The sledge was lowered to the ice, but the speed of undercutting had been under-estimated, and the sledge broke its way through before it had travelled 100 yards from the ship's side. Indeed the rotting had proceeded so far that the ice in many places would not bear the weight of a man, and two or three duckings were the result.*

This rotting from below, which is of such great importance in the destruction of the ice, is known as " undercutting " (Plate CCXLV); and its antithesis, " overcutting " is to be seen where a swell is breaking along the edge of a sheet of sea ice, in a bay where the ice is heavily covered with snow. The snow is removed much faster than the ice beneath it, and the latter is left as a submerged tongue, which sometimes projects for a distance of several yards.

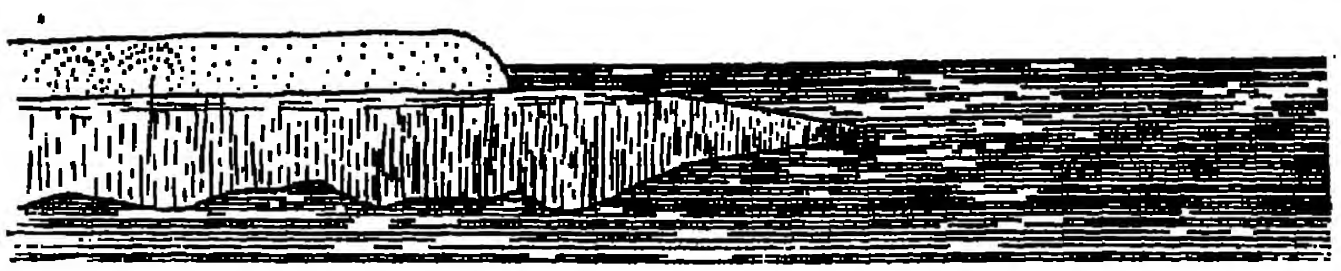


Fig. 166.—Example of " overcutting " seen at the Bay of Whales, in February, 1911.

A good example of this was seen at the Bay of Whales, in February, 1911, and this is illustrated diagrammatically in Fig. 166.

While all the above phenomena may be seen in any single summer, the time and thoroughness of the dispersion of the Fast-Ice of the bays and coast of the Antarctic varies immensely from year to year, and must have some connection with the weather conditions in the respective seasons and during the preceding winter.

If McMurdo Sound, which has been studied longer than any other portion of the Australian sector of the Antarctic, be considered, we find seasons ranging between that of 1902–3, when the ice only broke back to within 4 miles of Hut Point, and 1907–8, when it had all been removed before the close of the big gale of February 17—19, 1908.

* It is under circumstances such as these that the herds of killer wales take a somewhat prominent part in breaking away the ice. It is to their interest that the Fast-Ice should be broken up as suddenly as possible, since they find their prey upon it, and they know from experience that the quicker it goes out the less chance have the Weddell seals of anticipating the break and removing themselves to safer surroundings. On several occasions during the last two English expeditions these animals have been seen intentionally dispersing the fringe of rotten ice which, by diminishing the action of the swell and the thawing effect of the warm water, tends to retard the break-up of the ice in the bays and sounds.

(2) *Causes of the Break-up of the Fast-Ice.*—Let us now consider the main factors which go to prevent the permanent survival of a sheet of Fast-Ice in position. First of all, must be placed the effect of the tides which rise and fall regularly, and thus prevent any firm attachment to the shores of the bay. The tide-cracks formed by this movement are ever kept open, and, if it were not for the irregularities of shorelines and the presence of islands and stranded bergs, any single strong wind blowing off the land might carry the ice away with it.

The action of glaciers, as already indicated, may be either protective—where the Ice-Tongues extend from an exposed coast well out to sea, and where they are even-sided and movement is slight—or, on the other hand, may be disruptive when, as in the case of the Mackay Glacier, the Ice-Tongue extends out from the back of a bay and is moving forward comparatively rapidly.

The other agencies which produce lines of weakness in the ice have been mentioned already; they are pressure, temperature changes, and wind. The cracks between the pressure waves are especially efficient in the partition of the ice-sheet, while the cracks due to temperature changes are also marked lines of weakness.

Thus, we have in the sea ice a network of cracks which aid the disrupting action of winds, currents and swell from the open sea. The dispersal of the pack by rise of temperature, wind, current and swell, leaves the field free for operations on the Fast-Ice of the bays, and it is the break-up of this ice which falls within the province of this chapter.

The forces in action are of two kinds—those which break up the ice and those which remove it, thus exposing fresh tracts to the influence of the disrupting forces.

This latter work is largely carried out, in the Ross Sea area, by the violent winds and by the current which flows northwards along the coast of South Victoria Land. The work of disruption may also be partially effected by the strong off-shore gales, but by far the greater amount must be put down to other causes.

This particular portion of the life-history of the sea ice has always been closely watched by expeditions in every portion of the Antarctic, because their chance of relief or detention is intimately bound up with it. It has been noticed again and again, that, while during southerly gales and even during calm spells, pieces of ice, sometimes of considerable size, break off from time to time and move north, it is on occasions when a swell makes itself felt from the north (the direction of the open sea) that mile after mile of apparently unbreakable ice moves out as regular rectangular floes, whose size is possibly dependent upon the amplitude of the swell.

It is impossible to cite a more instructive example of this action than the occasion when, on February 14, 1904, several miles of two-year-old sea ice broke out in the course of 24 hours, thereby freeing the "Discovery" for the first time since March, 1902.

It will be seen from this discussion that the one feature which is most favourable for a rapid dispersion of the Fast-Ice in the Ross Sea area is the absence

of any considerable belt of pack to the north to deaden the influence of the swell from the open sea.*

Plates CCXLVI and CCXLVII show different methods of dispersion of fast-ice.

* There seems little doubt that, at least at Cape Evans, tidal currents played an important part in the break-out of the ice. It is easily seen that the effect of spring tides in weakening the force holding the ice in the bays to the shore must be considerable, for the movement at the tide-cracks is much accentuated at these times. This effect, however, is more or less local and insufficient to explain the dispersion of the seaward portions of ice which may lie far from the land. It seems more than probable that at spring tides large volumes of warmer water enter McMurdo Sound and notably accelerate the rate of melting of the ice from below. Both in 1911 and 1912 the open water was never far distant from Cape Evans, and, in both years, it was found that the dates on which the ice moved out generally corresponded with the time of the moon's maximum declination. Nelson states that in the winter and spring of 1911 the current, as judged by the set of lines at his holes through the sea ice, was between north and west, no indication of a southerly current being observed until December 3. On this day the current was observed to be running strongly to the south. This change in direction of the current as summer approaches is thought to be of great significance to the break-up of the Fast-Ice in McMurdo Sound. Measurements of velocity and direction of the currents in South Bay during December, 1911, by Nelson, also make it clear that the greatest movements of sea water take place about when the moon has its maximum declination.

CHAPTER XI.

ANTARCTIC PACK-ICE.*

(a) *General Discussion of Antarctic Pack.*

The Antarctic pack may be defined as a medley of ice composed partly of sea ice frozen in the open sea, partly of broken-up remnants of the Fast-Ice formed along the Antarctic coastline, and partly of the seaborne detritus of land ice from the Antarctic continent and islands. Amongst its constituents are included fragments of ice ranging through every gradation from huge bergs and floes many miles long and broad, to the ice-crystals which are the first product of the supercooling of the sea, or the brash and slush which are the ultimate solid residue of the disintegration of waterborne ice of all descriptions. The greater portion of the Pack-Ice has its origin at or near the shores of the continent and islands, but the main ice-girdle lying further off the coast is constantly being fed from this reservoir, the agents causing the northward drive being the radial circulation of the lower strata of the atmosphere with an easterly component due to the earth's rotation. These winds, with a predominantly south-easterly direction, cause a constant and comparatively steady drift to the north and west.

This drift might be expected to crowd the southerly shipping lanes with drifting ice, or even to drive masses of ice right up on to the shores of the more southerly extending continents. That this takes place only in very exceptional years is due to another limiting factor—the westerly air circulation of the middle latitudes of the southern hemisphere.

Between 40° and 60° S. latitude, these boisterous winds blow steadily from a direction varying between W.N.W. and N.N.W., effectively neutralising the northerly drive given to the Antarctic pack by the southerlies of higher latitudes. Not only is the northward progress of the pack effectively limited, but such a measure of consolidation is set up through the influence of the conflicting tempests (and the surface sea currents which they cause), that the *mélange* of ice forms a most effective barrier to the southward journey of ships endeavouring to make their way to the Antarctic continent. Before the advent of the steamship, it was largely a matter of good fortune whether any great progress to the southward would be made. The introduction of steam and internal-combustion engines, during the later years of the 19th and the earlier years of the 20th centuries, has to a great extent overcome this hindrance.

The increased possibilities thus opened up, have also assisted the modern navigator and scientist in elucidating to some extent the laws in accordance with which the ice-pack acts. Both these factors have done much to render ice navigation in polar latitudes

* Sea-ice definitions will be found on pp. 393–394.

less fraught with danger. Nevertheless, the fact remains, and has recently been amply demonstrated by the fortunes, or rather misfortunes, of the "Endeavour" and the "Aurora," that, under some circumstances, the Antarctic ice-pack can yet prove an impassable barrier even to modern ships, and that an error of judgment, or even a degree of ill-fortune, may lead to irreparable catastrophe.

Perhaps, from the navigational point of view, the most striking characteristic of the Antarctic pack, considered as a whole, is the westerly drift, the existence of which has been amply demonstrated in recent years. The cause of the drift is plainly to be sought in the controlling influence of the south-easterly winds. Observation of the pack in the north polar basin has long ago shown that wind plays a predominating influence in producing and controlling movement in free sea ice.

That wind direction is the direct cause of the main Antarctic ice-pack circulation has been proved several times by the drift of ships held voluntarily or involuntarily in the ice. On the map (Fig. 167) has been plotted a diagrammatic representation of the approximate courses of—

(*a*) The "Belgica" (Belgian Antarctic Expedition, 1898–99).
(*b*) The "Gauss" (German Antarctic Expedition, 1901–03).
(*c*) The "Endurance" and the "Aurora" (Shackleton Antarctic Expedition, 1914–17).
(*d*) The "Deutschland" (Filchner Expedition, 1910–12).

In all cases, the northerly and westerly movement of the pack, considered as a whole, is very marked, while the preponderance of the northerly component is clearly due to the shouldering off of the ice-pack by northward-extending projections of the continent.

In the case of the "Endeavour," the drift was at an average rate of 4 sea miles per day, while the "Deutschland," for some portion of the time during which she was imprisoned, reached a rate of 6 sea miles per day.

Less opportunity was fortunately given in the Scott Antarctic Expedition, 1910–13, to study in detail the movement of the pack; but, from the station at Cape Adare, the steady north-west movement along the coast of Victoria Land was well seen during the autumn, winter, and spring of 1911, while from the ship, on the several occasions when she was navigating through the pack, a general drift in the same direction was observed now to facilitate, now to hinder, the attainment of her immediate objective.

One particularly interesting piece of evidence was afforded by the subsequent history of a berg formed by the breaking away of 2 or 3 miles of the seaward end of Glacier Tongue in McMurdo Sound. This ice-tongue was easily identifiable, because it happened to have upon it a depôt of pony fodder which had been left by Shackleton in 1908. Captain Scott, with a sledge party, when making their way along the west coast, in September, 1911, came across the remains of this berg north of Cape Bernacchi. Since March of the same year, the tongue had travelled from a point 5 miles south of Cape Evans to 40 miles W.N.W. of the same point. When the Northern Party sledged down

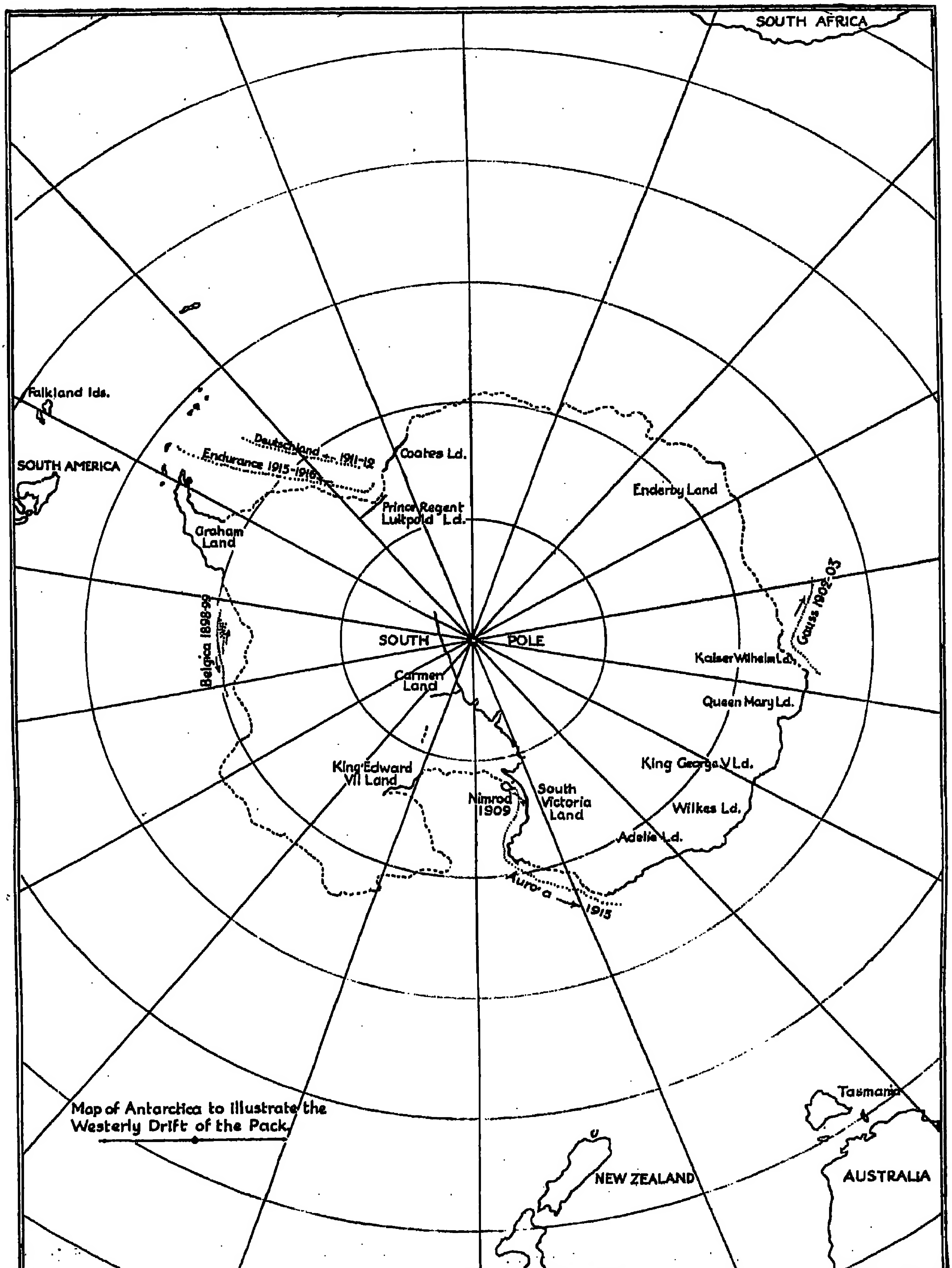

SOUTH AFRICA
Falkland Ids.
SOUTH AMERICA
Deutschland 1911-12
Endurance 1915-1916
Coates Ld.
Prince Regent Luitpold Ld.
Enderby Land
Graham Land
Belgica 1898-99
SOUTH
POLE
Gauss 1902-03
Kaiser Wilhelm Ld.
Carmen Land
Queen Mary Ld.
King Edward VII Land
King George V Ld.
Nimrod 1909
South Victoria Land
Wilkes Ld.
Adelie Ld.
Aurora 1915
Map of Antarctica to illustrate the Westerly Drift of the Pack.
Tasmania
NEW ZEALAND
AUSTRALIA

Fig. 167.

the coast in November, 1912, the berg had disappeared and was doubtless many miles on its journey towards the north and the open sea.

In the Shackleton Expedition, 1907–9, the "Nimrod," in January, 1909, was beset in the pack off Horseshoe Bay on the coast of Ross Island, and was carried across to the neighbourhood of the Nordenskjöld Ice-Tongue before she could extricate herself. Further evidence might be cited from Adélie Land, where the Mawson Expedition also saw much of the ice-belt at close quarters.

The deduction of most value which arises from all such observations is the generalisation that passage to the shores of the Antarctic continent must necessarily be most difficult of access immediately to windward of prominent points of land or ice-tongues. In the Ross Sea, for example, the avoidance of the west coast has been a matter of common practice from the beginning of the present century. To this practice is due the fact that, until the case of the "Aurora," no instance had occurred in this sea of a ship being dangerously nipped in the main ice-stream passing close along the coast of South Victoria Land. Risks have had to be taken on occasion, but every care has always been exercised during the attempts to land parties upon, and to explore from the ship, that portion of this coast north of the Ross Sea where danger is most likely to occur.

While the direction of the prevailing wind is the outstanding factor causing Pack-Ice movement, three other influences which have a minor but important effect must be recognised. These are:—

(*a*) A westerly component of drift due to the earth's rotation.

(*b*) The effect of deep currents on the icebergs which form no inconsiderable portion of typical pack.

(*c*) The obstructive effect of prominent points along the Antarctic coastline.

(*a*) That the first of these three factors does have a decisive effect upon the movement of the ice-pack has been proved by J. M. Wordie* in his paper embodying the observations on the Pack-Ice of the Weddell Sea, made during the drift of the "Endurance" in 1916. The fact that the westerly drift against the wind also took place towards a lee coast makes it still more significant. In any future attempt to calculate from more complete data the movements of the pack, this factor must be taken into account.

(*b*) One of the features of an ice-pack is the extreme heterogeneity of the fragments of which it is composed. It is this heterogeneity which, beyond all other things, prevents the freezing of the fragments together to form a solid mass during the colder portion of the polar year. It follows naturally that this characteristic is of extreme importance in determining both rate and freedom of movement, and passage round the obstacles which so frequently obstruct its course. A solid ice-pack of homogeneous constitution would be a much more compact obstacle in the navigator's path. It would also be very slow to move north, and would be more likely to become permanent by increments of snow.

* Shackleton Antarctic Expedition, 1914–17: "The Natural History of Pack-Ice as observed in the Weddell Sea." J. M. Wordie, 'Trans. Roy. Soc. Edin.,' vol. 57, part 4.

Within the ice-pack, there are at least three distinct elements which present a radically different degree of oposition to wind and current. There are the floes of Level-Ice, hummocky-floes, and icebergs. It is the last of these three which are chiefly affected by the deeper currents, as opposed to the surface drift of the sea water which is controlled by the winds. The sight of bergs moving in an apparently different direction from the main pack is a common sight in the Ross Sea. In some cases there is an actual difference in direction; in others, the appearance is due to different rates of movement in the same direction. From one point of view, this differential movement has a very decisive effect on the composition and stability of the pack. Not only does the resultant movement much increase the proportion of pressure ice to flat pans, but, in addition, open pack is made much more navigable by the continual surging to and fro of these more massive elements. On the other hand, the presence of large numbers of icebergs in close pack, especially in a pressure area against a coast, is one of the greatest menaces to the navigator which Pack-Ice presents.

(c) The third factor limiting the controlling action of the winds is of paramount importance in the case of navigation alongside a coast for surveying purposes. It has an even more important bearing on the fortunes of the Antarctic Expeditions of the next few years than on those of the past. Those portions of the Antarctic continent at all well-known are those most easy of access. Pack-Ice is certain to give more trouble in those areas where it has, so far, entirely prevented near approach to the coastline.

The greatest amount of danger from pack exists in an enclosed space. A narrow strait or a deep bay into which the wind blows directly is of course the worst of all positions. Nevertheless, the area to windward of a prominent point in the coastline can be almost equally dangerous. A sudden change or increase of wind may cause a ship to be beset in a few minutes. Pack which is close enough to be impenetrable merely wants a little extra pressure to make it dangerous, while pack on a lee shore may always cause disaster, even if pressure is not sufficient to cause actual crushing of the timbers of a ship.

A special class of obstruction which is peculiar to the Antarctic is that provided by the many Ice-Tongues which protrude at intervals along the coast of all known Antarctic lands, and which are perhaps the most striking formations characteristic of the present stage of the Antarctic glacial cycle. From the point of view of the navigator of Antarctic seas, they are the greater menace, because, while often extending many miles out to sea, they bear no fixed relation to the trend of the coastline. It is in respect of these tongues that the recent observations upon the drift of the main Antarctic pack may be most useful. The presence of such a tongue to leeward may be inferred with some certainty if no other sufficient reason, such as shoal water or a seaward extension of the true coastline, exists to account reasonably for an ice-jam along an otherwise clear coast.

(b) *Origin of Pack.*

In so far as the Antarctic pack is composed of fragments derived from land ice formations, from the icefoot and from sheets of Fast-Ice, its origin has been

comprehensively dealt with in previous chapters. A great proportion of the ice, however—and this appears to be greater in the Weddell Sea than in the Ross Sea—is formed in the open sea, and is thus exposed to somewhat different conditions from the Fast-Ice of more southern latitudes.

The difference as observed in the Ross Sea can be summed up in two or three particulars, all of which have been recorded for Weddell Sea pack by J. M. Wordie, and all of which appear to operate to a somewhat greater extent in the area studied by him.

If we compare the conditions under which sea ice freezes, in the coastal strips and bays where Fast-Ice normally forms in the autumn and early winter, with those under which ice forms in the pack in the open sea at more northerly latitudes, two or three differences will at once become obvious. In the one case, the ice freezes in comparatively large sheets, in water free from previously formed ice, except for occasional bergs and heavy stranded floes. In the pack, on the other hand, formation goes on mainly in restricted areas, often full of slush, and usually of rather elongate form. With this habit may be correlated the occurrence of rather aberrant modes of formation, as, for instance, the growth of the top layer as fan-shaped bundles of plates set vertically in the water, as opposed to the more normal horizontally disposed crystals which usually form the upper layer of ice where large stretches of open sea have frozen over. It is along ice edges such as the one mentioned by Wordie, in citing his type case, that such specially disposed groups of crystals are to be expected. They will seldom occur where there is no rigid support for them to grow from, though this mode of formation in a large sheet has been seen many times in McMurdo Sound. In the pack, the length of ice edge along cracks is great in comparison to the amount of open space at any one time. It is, therefore, only to be expected that this method of formation will be much more common (where the crack is free from brash ice), while another predisposing cause is the absence of wave action which must also be a feature of such narrow leads and cracks.

Ferrar's observations regarding the normal method of formation of the upper layers of ice in open spaces of water is borne out by our own experience. The tendency quite clearly is for the crystals to form in a vertical position if they have the necessary support such as is afforded—in the case of ice forming in a lead—by the solid ice edges already existent; in the case of ice forming in the open sea—by the initial layers of crystals horizontally disposed. In the latter case, until the initial layer is formed, it is extremely unlikely that single crystals will remain vertical, as there is almost always a certain amount of movement in the water. An exception to this rule which has been observed to take place occasionally in very calm weather, is where bundles of horizontally disposed crystals form the nuclei around which groups of vertically arranged crystals are disposed. This gives rise occasionally to stretches of very beautifully mottled ice, the wedge-shaped bundles with different orientation showing up particularly well on ablation-weathered surfaces (Plate LXXVI).

Similarly, another mode of formation, that of the out-growth of single large crystals or lines of crystals from the sides of cracks, which was observed several times near the

edge of the Fast-Ice sheet at Cape Adare and Cape Evans, is much more common in the pack than in Fast-Ice.

An abnormal type of ice, which appears to be formed in the pack as well as in Fast-Ice, is characterised by horizontal layers of bubbles at intervals of from a quarter of an inch to an inch, or more. Such a concentration of air along definite horizontal planes is susceptible of several explanations, and such ice is probably formed in several different ways. The formation of layered ice by overflow along the edge of tide-cracks has already been referred to elsewhere. Similar ice is doubtless formed in great quantity as an incident in the formation of small pressure floes, such as that figured in Plate CCXLVIII. In such cases, concentration of air along the dividing planes, if it does not occur at the time of formation, is quite likely to take place to a greater or less extent during later structural changes.

Another way in which layered ice frequently has been observed to form is when the sea is just commencing to freeze in the early autumn. At this time, it is usually only for a few hours in each day that freezing takes place. During the remainder of the time, freezing ceases and melting may even predominate. At such times, certainly, concentration of gas does take place immediately underneath the ice-skin. The air thus concentrated is subsequently entangled among the next crystals formed, and is finally frozen in as a more or less well-defined layer of bubbles. Ice formed in this way has been observed with a dozen to fifteen well-marked layers. It seems reasonable to infer that, at times, ice of similar nature will form in the pack belt itself.

Yet another method by which layered ice is likely to be formed in any region where pressure and tension exists, is by the bowing of young ice, a slight change of equipoise resulting in the raising of a sheet of very young ice above the water and the trapping of a certain amount of air beneath it. A release from tension will allow the ice to settle down more or less completely, and the air will be (partly, at least) incorporated in the new ice as a layer of bubbles. The existence of air in pockets under ice has been often enough demonstrated (Chapter X, Page 343).

A special feature which affects Pack-Ice, in greater degree than the Fast-Ice, of the Ross Sea area, is the amount of precipitation which takes place during its normal life-history. This may be considered in terms both of condensation of water vapour from the air as hoar-frost and of snow as generally understood. In latitudes 60° S. to 70° S., within which geographical limits the ice of the Antarctic pack spends the greater portion of its existence, the snowfall is undoubtedly heavier than along the coast of South Victoria Land where the Fast-Ice of the Ross Sea area has been closely studied. The amount appears to vary widely even within these geographical limits and also in terms of longitude. For instance, Drygalski ascribes much more importance to the growth of Antarctic sea ice from above than does Wordie, while the scanty records from the Ross Sea would serve to suggest that here, near the southern limit of the pack belt, the snowfall is much less than in either of the above places. This is perhaps only to be expected when one compares the relative degree of glacierisation of Adélie Land with South Victoria Land, and of the Balleny Islands, or any other islands at about this

latitude, with the islands close to the continent further to the south. That a comparatively large amount of snow falls in the latitudes where the westerly ocean air circulation meets the southerly continental air circulation seems to be certain.

Another factor which must tend to bring about both a greater fall of snow, and an almost continuous deposition of hoar-frost from the air, is the fact that new spaces of open water are continually being exposed even during the coldest months of the year. In this respect, the contrast between Pack-Ice and Fast-Ice was extremely well seen at Cape Adare.

This peninsula is the north west boundary of the Ross Sea proper, while it forms also the eastern boundary of Robertson Bay in which Fast-Ice is every year typically developed. During the winter, openings in the Fast-Ice of the bay are few and far between, being limited to temperature contraction cracks, or to cracks caused by the movements of bergs. Being of very small extent, these cracks usually close over very quickly, and, though frost-smoke sometimes outlines them for a few hours, they can have had little effect on the vapour-content of the atmosphere as a whole.

Far different, however, was the case to the east, north and north west, beyond the confines of the bay. Here, the main Antarctic ice-pack impinged against the continent after its westerly drift round and across the mouth of the Ross Sea. Every day new cracks appeared; at times of gales, the cracks, pools, and leads within sight of the top of the cape might be numbered in dozens. Occasionally a great catastrophe would tear the ice across like a sheet of paper, leaving a belt of black water a mile or more broad at its eastern end and narrowing until it died out towards the west coast as one or more linear cracks. Every lead was covered for days with a dense canopy of frost-smoke. Heavy rolls of cumulus cloud to the northward attested daily to much more important breaks in that direction.

When northerly airs blew from the affected region over the beach at Camp Ridley, every ice-block along the icefoot was covered with a layer of ice-crystals of that powdery granular appearance which always accompanied rapid deposition from a saturated atmosphere. Every rope, every bamboo survey stake, would be covered to windward with frost crystals. The air had that peculiarly "raw" feel, which was never experienced except when it was at or near saturation point. Ice-flowers grew rapidly on all possible salt nuclei, and sometimes so quickly as to become converted into veritable ice-knobs.

A glance into the bay at such a time would show the reverse side of the picture very well. It was seldom that the saturated air penetrated very far to southward of the beach. What little deposition was accomplished was quickly neutralised in the first few minutes of the next southerly wind. Here, as in almost all other Fast-Ice regions in the Ross Sea area, the predominant factors affecting the surface of the sea ice were ablation and drift-chiselling. Certainly, the ice received no great accession from above; often it was being worn away comparatively rapidly, a polished ice surface being the result. This would indeed have been much more the case, but for the clogging action of the brine particles on the surface of newly-formed ice, which converted the first coating of snow into the

salt, sticky, tough aggregate known to the sledge traveller as "salt-flecked" surface. It was usually some weeks or months before this dried sufficiently to permit its removal.

In spite of this slight conservative influence, however, even at Cape Adare, where snowfall was a factor common both to Pack-Ice and Fast-Ice, the constant deposition from a saturated atmosphere over an ice-field continually opening to expose fresh leads and pools was sufficient to give quite a different appearance and character to the latter. Hollows in the pressure ice were filled with snow, and the ice altogether had a much more snowbound appearance. Growth from above was a notable factor as explained in Chapter X. This was apparently much more the case in the Weddell Sea. Here Wordie records no single day without excess of deposition over ablation. Drygalski,* again, in his discussion of the Pack-Ice off Kaiser Wilhelm Land, refers to the addition of as much as 5 to 7 metres to the floes surrounding the "Gauss," a figure out of all proportion to the deposition observed in the Ross Sea.

The ice in the main pack-belt must, therefore, grow appreciably from above; while the lower latitude which it inhabits after leaving the shores of the continent ensures also a comparatively slow growth below, as compared with Fast-Ice. Pack-Ice of more than one season's growth might thus, quite conceivably, contain a negligible amount of ice which was formed by the freezing of sea water. The summer temperature of the sea will often quite suffice to melt a winter's accumulation of sea ice, particularly in favourable situations. When, however, fresh ice is being formed by the addition of several feet of snow and its penetration by sea water percolating from below, a residue is likely to survive into next year. Our own experience of Ross Sea Fast-Ice and Pack-Ice is that it normally lasts through one season only, with the exception of that formed in certain of the deeper bays, or the small amount formed in other peculiarly favourable situations, as where it is protected by shoal water, islands, or icebergs. Wordie's experience in the Weddell Sea suggests a normal life of two years for the pack in the track of the "Endurance" and the boat parties. Von Drygalski claims a much greater age for the pack met by the Gauss, and this, if correct, must be correlated with a greater snow-fall and consequent quicker addition from above.

(c) *Special Consideration of the Ross Sea Pack.*

Apart from the passages of the "Terra Nova" south and north, which were made approximately between the meridians of 160° E. and 170° W. longitude, the *points d'appui* from which members of the Expedition had opportunity of observing the character and the movements of the Ross Sea pack were—from east to west—Cape Crozier, Cape Royds and Cape Evans, Granite Harbour, Terra Nova Bay, and Cape Adare. Observations from all these points agree in emphasising the correctness in principle of the westerly circulation of the pack in the Ross Sea area. Where the ice stream crosses the mouths of deep bays, such as McMurdo Sound and Robertson Bay, or passes the snout of ice-tongues, such as the Drygalski and the Nordenskjöld Ice-Tongues, this simple circulation is complicated by the existence of eddies. These delay the northward

* *Loc. cit.*

progress of a small proportion of the floes, and often prolong their life by throwing them into a backwater or natural trap in which they are caught up again in the next season's Fast-Ice.

The only special feature affecting the circulation in the Ross Sea is the undoubted existence of a current flowing from underneath the Ross Barrier, past the shores of Ross Island and up the coast of South Victoria Land, where its presence may be inferred from the persistence of the waterholes in the lee of the ice-tongues mentioned above. (See Chapter X.)

The experience of different steamships endeavouring to make their way into the Ross Sea varies from that of the "Nimrod" in January, 1908, which saw practically no pack, to that of the "Terra Nova" in December, 1910, which was 30 days forcing her way through. On the map, Fig. 168, an endeavour has been made to plot diagrammatically the breadth of the belt of pack as encountered on different dates, in different years, and in different positions, by the various ships that have endeavoured to penetrate the Ross Sea. The diversity of the dates and tracks, and the lack of knowledge, in the majority of cases, of the weather of the preceding years, militates very much against the possibility of drawing valuable deductions. The facts should be placed on record, however, in available form, if only to avoid repetition of the work of the present compilation. In the same way, Table XIV gives for each outward voyage the latitude and longitude of entrance and exit from the pack, together with the appropriate date.

As an example of the unexpectedness of some of the factors entering into the problem, the extreme case of the "Nimrod" in 1908, may be cited. The ship sailed for many hours through immense fleets of tabular bergs at about the time and latitude when it might have been expected that she would meet the pack. It is extremely likely that the absence of pack on this occasion should be correlated with the presence of these bergs, which can only have arisen from the breaking away of a large stretch of the Ross Barrier. The subsequent survey brought to light, among other things, the disappearance of Balloon Bight, the walls of which were low and might well have been represented by the cliffs of some of the bergs seen. This extraordinary absence of pack at the entrance to the Ross Sea has since been paralleled by the experience of the "Aurora," which, on its outward voyage with Shackleton's Ross Sea Party in 1914–15, passed through only one mile of pack.

As early as 1898, Borchgrevinck gave instructions to the captain of the "Southern Cross" to bring the ship down further to the east than her first voyage had been made. This was a practical result of his own experience. The principle was more and more exploited as the years passed until, finally, Pennell brought the "Terra Nova," in 1912–13, so far east as to touch 160° W. longitude.

The information summarised in Table XIV has been plotted in Figs. 169 and 170 to display the results up to date, so far as possible in graphic form. In both figures the centre of the plain circles represents the date and position—in the one figure, longitude; in the other, latitude—on and in which the ship entered the pack. The centres of the blackened circles similarly show the dates and positions on and in which the main

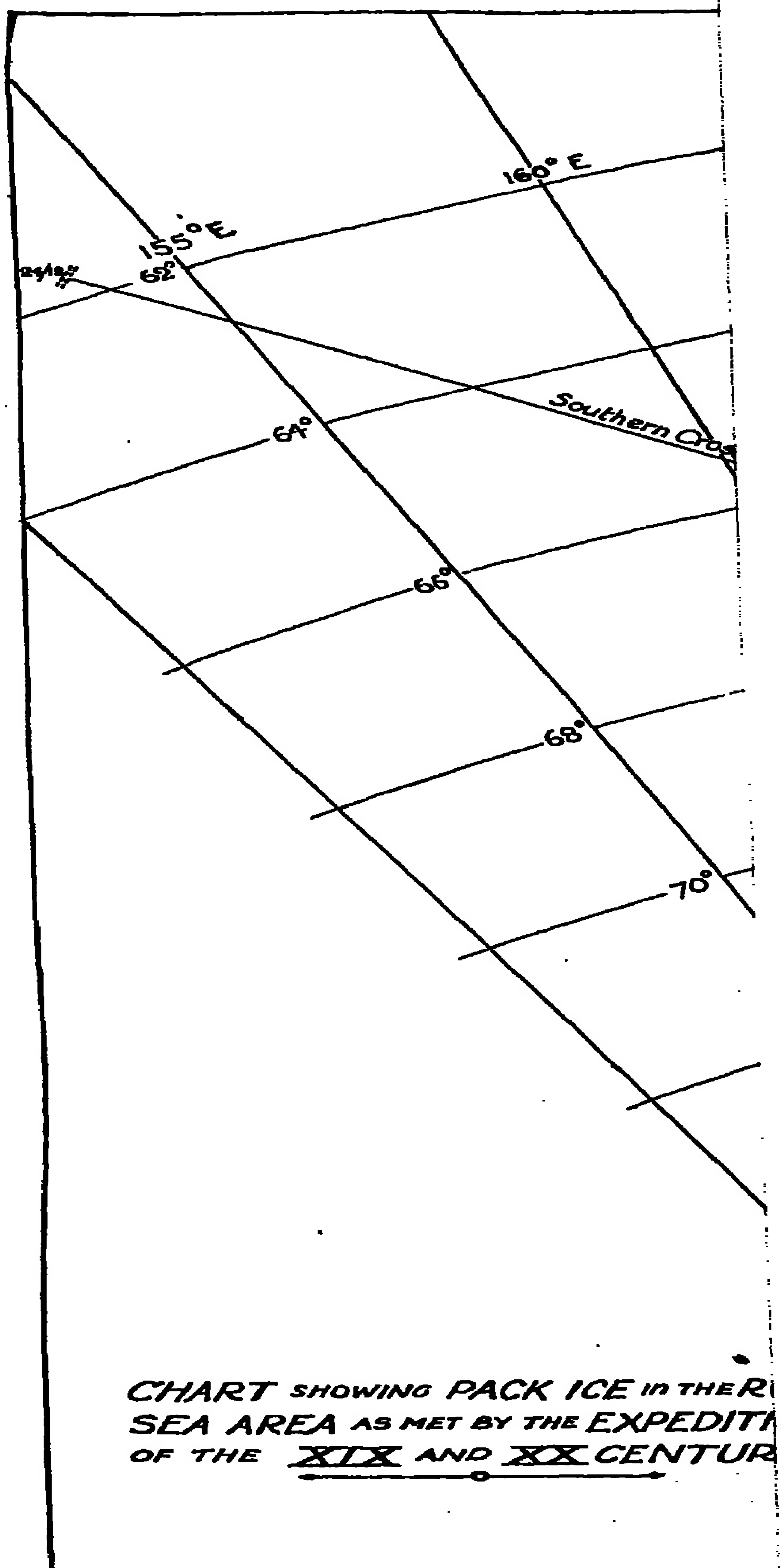


CHART SHOWING PACK ICE IN THE R
SEA AREA AS MET BY THE EXPEDITI
OF THE XIX AND XX CENTUR

TABLE XIV.—N. and S. Limits of Pack in the Ross Sea.

Date of Entry.	Latitude.	Longitude.	Year.	Ship and Expedition.	Date of Exit.	Latitude.	Longitude.
January 5 ...	66° 50′ S....	174° 34′ E. ...	1840–1841...	"Erebus" and "Terror," Sir James Clark Ross's Expedition.	January 9 ...	68° 45′ S. ...	176° 15′ E.
December 18 ...	60° 50′ S. ...	147° 23′ W. ...	1841–1842...		February 1 ...	67° 18′ S. ...	158° 12′ W.
December 8 ...	65° 47′ S. ...	171° 30′ E. ...	1891–1892...	"Antarctic," Captain Bull... ...	January 13 ...	68° 12′ S. ...	176° 59′ E.
December 16 ...	61° 56′ S. ...	153° 53′ E. ...	1898–1899...	"Southern Cross," Borchgrevinck	February 2 ...	70° S. ...	174° E.
January 3 ...	67° S. ...	178° E. ...	1901–1902...	"Discovery" National Antarctic, 1902–1904. (Captain Scott)	January 8 ...	70° 10′ S. ...	173° 30′ E.
December 24 ...	66° 20′ S. ...	180° E. ...	1902–1903...	"Morning"	December ? 31 ?	69° S. (est.)	180° E.
December 25 ...	66° S. ...	179° 30′ W. ...	1903–1904...	"Morning"	January 1 ...	70° 20′ S. ...	178° 30′ E.
January 14 ...	63° 59′ S. ...	179° 47′ W. ...	1907–1908...	"Nimrod," Shackleton Antarctic Expedition, 1907–1909.*	January 16 ...	68° 06′ S. ...	179° 21′ E.
December 20 ...	66° 30′ S. ...	178° 28′ W. ...	1908–1909...		December 22 ...	68° 20′ S. ...	175° 23′ E.
January 2 ...	66° 30′ S. ...	176° E. ...	1910–1911...	"Fram," Amundsen South Pole Expedition, 1910–1912.	January 6 ...	70° S. ...	180° E.
December 28 ...	65° S. ...	171° 30′ E. ...	1911–1912...		January 5 ...	73° S. ...	179° E.
December 9 ...	65° 8′ S. ...	177° 41′ W. ...	1910–1911...	Scott's last "Terra Nova" Expedition, 1910–1913.	December 30 ...	72° 17′ S. ...	177° 09′ E.
December 27 ...	63° 31′ S. ...	173° 23′ W. ...	1911–1912...		January 6 ...	68° 44′ S. ...	178° 35′ E.
December 29 ...	69° 28′ S. ...	166° 15′ W. ...	1912–1913...		January 16 ...	74° 50′ S. ...	177° 15′ E.
January 5 ...	66° S. ...	174° E. ...	1914–1915...	"Aurora," Shackleton Trans-antarctic Expedition, 1914–1917†.	January 5 ...	66° S. ...	174° E.
January 2 ...	70° 20′ S. ...	175° 20′ E. ...	1916–1917...	"Aurora"	January 7 ...	72° 04′ S. ...	175° E. ?

* No real pack met with; fleets of bergs only.

† One mile of pack only encountered.

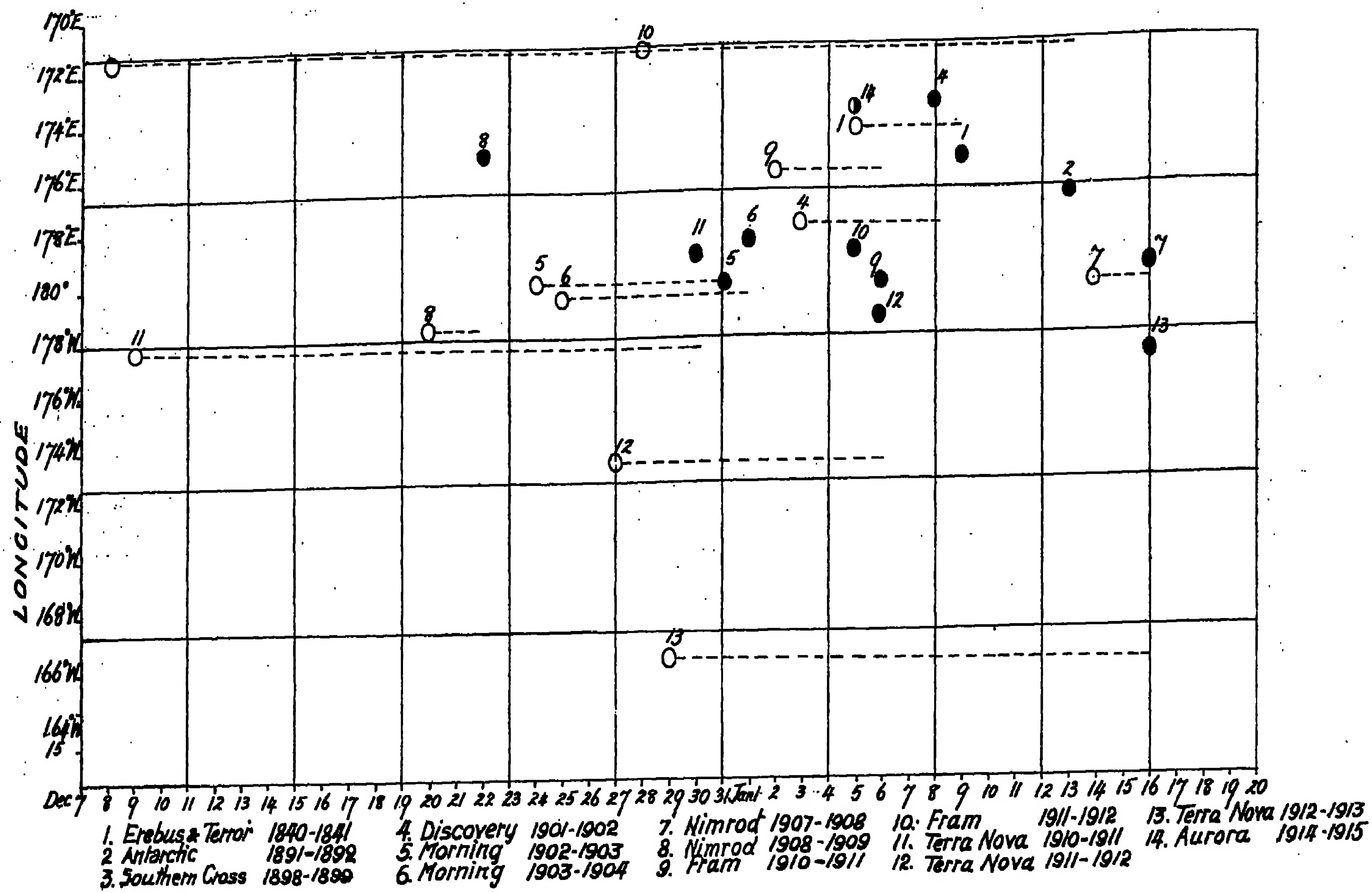

LONGITUDE
170°E.
172°E.
174°E.
176°E.
178°E.
180°
178°W.
176°W.
174°W.
172°W.
170°W.
168°W.
166°W.
164°W.
15
Dec 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 Jan 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1. Erebus & Terror 1840-1841
2 Antarctic 1891-1892
3. Southern Cross 1898-1899
4. Discovery 1901-1902
5. Morning 1902-1903
6. Morning 1903-1904
7. Nimrod 1907-1908
8. Nimrod 1908-1909
9. Fram 1910-1911
10. Fram 1911-1912
11. Terra Nova 1910-1911
12. Terra Nova 1911-1912
13. Terra Nova 1912-1913
14. Aurora 1914-1915

Fig. 160.

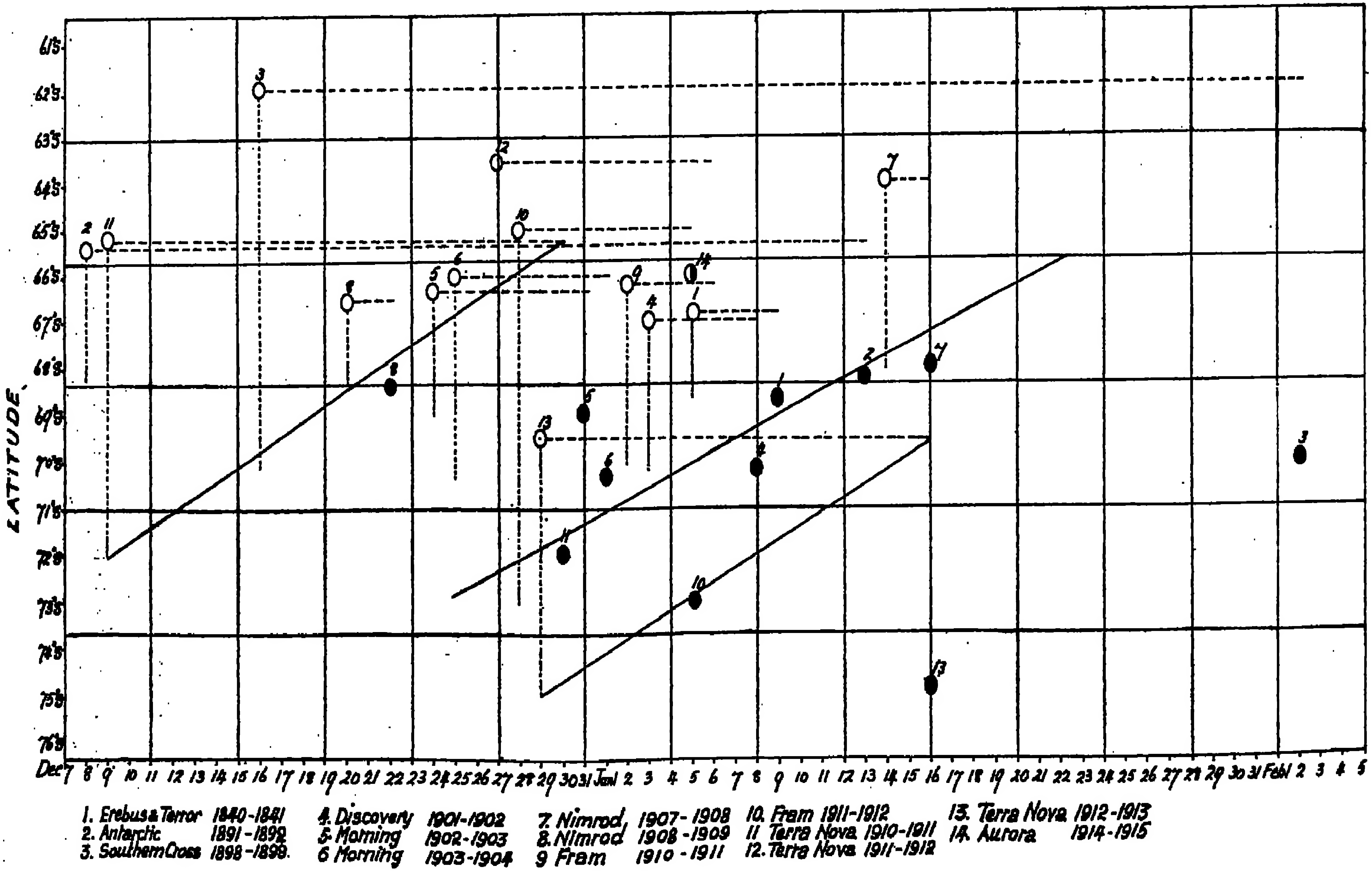

LATITUDE
61°S
62°S
63°S
64°S
65°S
66°S
67°S
68°S
69°S
70°S
71°S
72°S
73°S
74°S
75°S
76°S
Dec 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 Jan 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 Feb 1 2 3 4 5
1. Erebus & Terror 1840-1841
2. Antarctic 1891-1892
3. Southern Cross 1898-1899.
4. Discovery 1901-1902
5. Morning 1902-1903
6. Morning 1903-1904
7. Nimrod 1907-1908
8. Nimrod 1908-1909
9. Fram 1910-1911
10. Fram 1911-1912
11. Terra Nova 1910-1911
12. Terra Nova 1911-1912
13. Terra Nova 1912-1913
14. Aurora 1914-1915

Fig. 170.

pack belt was cleared. In Fig. 169 lines have been drawn horizontally from date of entrance to date of exit to show the length of time the ship was detained in the pack. In Fig. 170 still further information is given by plotting against similar lines, vertical lines showing the breadth of pack in latitude. Certain conclusions and inferences can be arrived at from these diagrams and these are tabulated below :—

(*a*) The first conclusion that can be drawn from Fig. 170 is, that the earlier the pack is met the longer will the ship take passing through it. With the single marked exception of the "Terra Nova" in 1912–13 (No. 13), the latitude of the northern edge of the Ross Sea pack appears to have been nearly independent of date. This is to be expected, as it is controlled by two factors, neither of which is likely to be much affected by time or season. The first of these is of course the geographical position of the coast-line of the continent, which shoulders off the pack to the north. The second is the position of the line of junction of the southerly and westerly air circulations which, while it probably does change its place at different seasons of the year, is not likely to do so during the few weeks under consideration.

(*b*) The date of leaving the pack in the normal case (tracks 1, 2, 4, 6, 7, 9, 11, 12) varies from December 30 to January 16. It will be seen that the latitude of leaving the pack is lower the later it is left, indicating a northward drift of its southern boundary (in about 176° E. longitude) of something like 200 miles in 15 days. This northerly drift is indicated by the full black line drawn along the general line of direction of the various points. The combined influence of the southerly component of the prevailing strong winds, of the Ross Sea current and of melting is able to crowd the southern edge of the pack northwards, in spite of any countervailing influences. Cases 8 and 13 are clearly exceptional, and 13, in particular, is undoubtedly to be associated with the weather conditions of the previous winter.

(*c*) A comparison of the horizontal and vertical interrupted lines in Fig. 170, shows that the speed through the pack is slower the earlier the pack is entered. This is to be expected since, the earlier the date, the less chance have the thawing influences of the Antarctic summer had to reduce the winter's accumulation with a consequent opening-up of the ice-belt.

The most notable exception is that of the "Antarctic" in 1891–92 (No. 3). This is readily accounted for, the "Antarctic" being a whaler and not primarily an exploring ship. Her captain's duty was the exploitation of new fishing grounds, and he was therefore more concerned with endeavouring to fill her hold with seal oil and skins than attempting with all possible speed to pass through a vexatious hindrance to extended exploration.

(*d*) At first sight, one of the most striking coincidences is that shown in Fig. 169, where all the ships are observed to have left the pack in the neighbourhood of 178° E. longitude. This is, however, an incident of exploration and bears no relation whatever to the lie of the pack-belt. It has happened that the objective of the great majority of ships entering the Ross Sea has been the south-west corner, where Ross Island and the Royal Society Range have offered the most promising sites for winter quarters and

detailed exploration, and whence runs the main highway to the Pole. This fact accounts for the convergence of the ship's tracks in the map, Fig. 168.

(*e*) A comparison of tracks 9 and 11, which refer to the same year (1910–11) should be of more than ordinary interest. Fig. 170 shows that the pack was met slightly further south at the later date. Fig. 169 shows that it was entered further west by the "Fram" than by the "Terra Nova." The difference both in latitude and longitude is slight, and the figures taken together appear to indicate that the northern edge of the pack in this neighbourhood remains about unchanged from early December to early January. Thus the inference is, that the northern edge of the pack neither changes very much from day to day, nor, as pointed out on p. 384, from year to year.

(*f*) From Nos. 10 and 12 it is apparent that the pack was entered by the "Fram" and "Terra Nova" about the same time, but at different longitudes. The inference is that the pack is met further to the north the further east one goes. This agrees very well with the presence of the belt of unexplored country to the north of King Edward VII Land, where the ice has been so thick that all attempts at exploration have so far been shouldered off. Somewhat against this conclusion, however, must be set the experience of the "Terra Nova" in the following year, which met no pack until latitude 69° 30′ S. was reached. This year was, however, clearly an exceptional one.

As one might expect from the fact that both these tracks leave the pack in the same longitude, they left it practically at the same time. Obviously, therefore, it is better to enter and traverse the pack at right angles to its northern boundary as did Nos. 10 and 9.

(*g*) A consideration of the latitude diagram (Fig. 170) and the longitude diagram (Fig. 169) seem to confirm that entry on the western side of 180° longitude is best in a normal year. The shortest passages have all been between that meridian and 176° E. longitude. It is possible that the pack is here slackest, due to an eddy in the Ross Sea, but the evidence is much weakened by the fact that, owing to a geographical accident, the objective of all ships causes them to leave the pack in about the same longitude.

A glance at the two tracks which keep well to the westward of the meridian (the "Fram" 1911–12 and the "Southern Cross" 1898–99) affords proof enough of the wisdom of keeping well to the east of Cape Adare, while this evidence is borne out, both from theoretical considerations of the westerly drift and from the experience of other cruises whose tracks are not included. With a general westerly set along the coast, Cape Adare and the coast to the north must always form the buttress against which an important jam has its existence. In the immediate neighbourhood of the cape, the surge of the tide in and out of Robertson Bay complicates matters. This inward and outward drive of the tide causes a rhythmical interruption in the main circulation at the entrance of the bay. Alternately, it makes the beach at Cape Adare, at ebb-tide, a possible objective for a landing-party, while at flood-tide it opposes great obstacles to the disembarkation of stores, and, at times, exposes a ship so engaged to considerable danger. Only in very favourable spells of light westerly or calm weather

will it be safe to venture close to the coast to the west of Cape Adare, from which prominent ice-tongues yet unmapped may project to form traps for the pack sweeping along parallel with it.

The only voyage very far to the east in the Ross Sea is that of Pennell in the "Terra Nova" in 1912–13. The fact that the pack was not met until 69° S. latitude augured well for the success of the new departure, but the year was a most unfavourable one for experiment, and the ship subsequently found herself involved in local Ross Sea pack from that latitude to as far south as 75° S., an unprecedented latitude in which to clear the pack.

In a normal year, the Ross Sea pack could not have remained so far south as 75° S. until January 11. The unfavourable year undoubtedly stultified Pennell's experiment, and it has still to be proved whether, normally, the 166th to 170th meridians of west longitude may not be a good direction from which to start the westerly journey towards the Victoria Land coast. It must be admitted, however, that Ross's experience in 1841 strongly suggests the neighbourhood of 180° as the better of the two, for the "Erebus" and "Terror" followed the pack edge from the eastward and found it impenetrable in longitudes east of the latter meridian. Moreover, there are certain indications that the pack belt normally runs, not east and west, but with a slope to the north-east, so that Pennell's course would naturally take him through a greater thickness of pack. An exception to the above generalisation would perhaps be furnished in the case of a particularly stormy spring at a time when there had been no great accumulation of ice. Then the Ross Sea ice might be disposed of as quickly as it was broken up, and Cape Adare and the west coast of Victoria Land be particularly easy of access early in the year. Possibly the success of the "Discovery" in penetrating to Wood Bay early in 1902 may have been due to such a favourable combination of circumstances. Something of the same kind must have taken place to enable the "Aurora" in 1915 to penetrate into the Ross Sea without meeting any pack at all.

The results of the many voyages seem to indicate that the pack varies from year to year more in accordance with the weather of the previous season than any other factor. Here, again, the data are very insufficient, such information as we possess being summarised in Tables XV. and XVI., which show the temperatures and wind velocities for several years.

The different stations—even those so close together as Cape Royds, Cape Evans and Hut Point—have their weather so far influenced by local conditions that little reliance can be placed on comparative statistics, except in so far as they refer to the same winter quarters in different years. For instance, the severity of the temperatures of the three stations mentioned above, which lie along a line almost north and south of the east coast of McMurdo Sound, depends distinctly upon their proximity to, or distance from, the open water of the Ross Sea, on the one hand, and the Ross Barrier on the other. In the future, however, these disparities may be eliminated to some extent by the application of a definite factor representing variation due to locality.

TABLE XV.—Monthly Mean Temperatures.

All figures degrees Fahrenheit.

Year.	Winter Quarters.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Yearly Mean.	Remarks.
1900	Cape Adare	+18	+10	− 5	−12	− 8·5	−13·5	−12·0	− 2	+18	+32	+33·8	+26·5	+ 5·4	"Southern Cross" Expedition.
1911	Cape Adare	+20	+ 9	− 0	−16	−15	−14	− 2	+ 2	+20	+28·5	+29*	+25*	+ 7·2	Scott's last expedition. *Estimated.
1908	Cape Royds	+ 5	−11	− 5	− 7	−17	−16	− 6	+ 4·5	+17	+30	+26	+20·5	+ 3·5	Shackleton Expedition.
1911	Cape Evans	+ 7	− 1	−11	−13·5	−21	−21	−16	− 3	+12	+22	+22·4	+19	− 0·35	Scott's last expedition.
1912	Cape Evans	+ 2·6	− 8	− 7·6	− 9	− 5·6	− 3·1	− 6·5	+ 3·5	+14·5	+24	+21	+13	+ 3·2	
1902	Hut Point	+ 8	− 7	−12·5	−16	− 8	−16·5	−12	− 8·5	+12	+23	+22·5	+16	+ 0·2	National Antarctic Expedition, 1901–1904.
1903	Hut Point	− 1	−17	−16	−14	−21	−16·5	−18·5	− 7	+15	+26	+26	+11·2	− 2·6	
1911	Bay of Whales ...	− 6·5*	−17·5	−31·5	−30	−33·5	−48·5	−35·5	−11·5	+ 4	+20	+14·5	+ 4·2	−13·5	Amundsen South Polar Expedition.

Table XVI.—Monthly Mean Wind Velocities.

All figures "Miles per hour."

Year.	Winter Quarters.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Yearly Mean.	Remarks.
1900	Cape Adare	8	5	3	5	3·5	3	3	3·5	3	6·5	8	—	3·7*	* Converted from Beaufort Scale.
1911	Cape Adare	8·7	6·9	15·9	3·6	2·9	6·5	13·2	4·3	4·2	6·3	4*	8*	7*	
1911	Cape Evans	25·6	15·9	12	13·2	18·5	16·7	14·5	17·9	16·1	14·7	10·9	20·5	16·3	
1912	Cape Evans	24·8	20·2	25	31·8	28·8	25·3	22·5	17·3	18·9	11·1	9*	22*	21·4	
1902	Hut Point	10	12	17	12	12	14	10	10	8	8	6	10	10·7	
1903	Hut Point	11	9	10	11	9	11	11	12	11	8	7	12	10·2	
1911	Bay of Whales ...	15*	9·8	6·5	8·9	10·5	9·2	9·8	14·5	11·4	10·7	7·8	15*	10·8	
1902	Kaiser Wilhelm Land	10·7	12·5	19·9	11·6	14·5	19·9	11	9·2	10·5	10·3	9·4	13·2	12·7	German Antarctic Expedition, 1902–4.

At present, enough is not known for this to be done, though the whole of the available information is included to serve as a basis for future comparisons. It is, however, possible to observe a distinct excess of wind in the period 1911–13, as compared with earlier years in the same localities. It might then be expected that these years would be correlated with a period of unusual difficulty in the navigation of the Ross Sea, and this proved to be the case. There is every reason to postulate similar conditions in 1909–10, when the "Terra Nova" was 30 days passing through the ice-belt. Certainly, in 1911–12 and 1912–13, navigation within the Ross Sea was rendered particularly difficult by the quantity of Pack-Ice. The direct result of this is seen in the failure to pick up the Western Party at the correct date and place, and the failure to pick up the Northern Party at all. The loitering of a large amount of pack in confined waters like the Ross Sea implies a general excess of pack all along the surrounding coasts, for otherwise the southerly gales of a stormy winter would soon drive the Ross Sea ice north. That this was so in 1911–12 and 1912–13, is borne out by the observations of the Mawson Expedition further to the north and west. The captain of the "Aurora," the ship of the Australasian Antarctic Expedition, reports a belt of pack off Adélie Land and King George V Land, which progressively increased in breadth and closeness from 1911–12 to 1913–14. There seems every reason to infer that conditions all over East Antarctica favoured the accumulation of Pack-Ice in these years. The weather ideal to such an accumulation is rather a stormy than a cold winter. Even cold such as was experienced in the Ross Sea in 1911–12 and 1912–13 is quite sufficient to freeze the sea surface along all coasts. Throughout the autumn, winter and spring, a calm spell of a week's duration will produce an ice-sheet of thickness sufficient to ensure its moving north and west in moderate sized floes not easily reduced to brash. A gale following such a short spell of calm will certainly blow such a sheet away. A few days of fine weather, and another gale—the usual sequence of Antarctic weather along steep coasts—will repeat the process. Imagine this going on through the 6 or 8 months of a stormy season along a coast thousands of miles in length, and it is quite clear that the amount of ice formed and held south of the "westerly" zone is likely to be more than can be dealt with by the normal melting of a single season.

In Robertson Bay alone, in 1911, which was the less stormy year of the two, ice sufficient to fill the bay at least five times over was formed and driven out before the final fast sheet settled in.

Off the mouth of the bay, and within sight of the top of the cape, the continual opening of leads and pools due to current and gales must have caused the formation of sheets of new ice sufficient to cover the area in view two or three times at least. Besides this must be counted the ice which was telescoped on already existing floes, in the form of pressure ridges and areas. This also enters into the problem to the extent of making the resultant pressure floes more resistant to denudational influences and therefore longer-lived.

Another factor which tends still more in such a season, or series of seasons, to

bring about unusual accumulation and persistence of ice, and hence greater difficulty of navigation, is the resultant damping of the swell from the north, which normally plays a most important *rôle* in the disintegration of the Fast-Ice along the coast of South Victoria Land. The sheet of Fast-Ice will be of less thickness than usual, because it settled in finally at such a late date. Nevertheless, it may remain for a longer period, if the Ross Sea is so full of pack that the swell is damped to a great extent. It is under conditions such that the winter's accumulation of pack is not dispersed until late in the autumn, that one would expect the survival of the coastal Fast-Ice from one year to another in favourably situated landlocked bays, or over iceberg-studded shoals.

One aspect of the problem, on which practically no direct evidence is available, is the question whether the surface of the main body of the Ross Sea is itself frozen over during the normal winter. In spite of the existence of stations, in 1911, all round the fringe of the sea from Amundsen's winter quarters at the Bay of Whales to our headquarters at Cape Adare, a glance at the map will show that the available evidence, so far as direct sight goes, is confined to a comparatively narrow fringe of shore water. The question of the state of the sea in winter is one on which we have indirect evidence only, and very little of that.

The freezing of the surface of a deep sea must always be rendered difficult by convection currents, and it is a nice question whether such a circulation might not well be sufficient to keep the surface unfrozen, in spite of the freezing of the shallower portions along a coast, or even over the continental shelf. In these shallower shoreward portions of the sea, convection is unable to overcome the direct cooling effect of the contact with the atmosphere. Even here, however, as is shown by the waterholes to the north of the Drygalski and Nordenskjöld ice-tongues, a geographical accident causing the uprising of the lower layers of the main Ross Sea current is sufficient to delay the local freezing of the sea for months — even in the case of Terra Nova Bay until the end of the winter.* In 1912, at Terra Nova Bay, the Drygalski waterhole remained open throughout the whole season.

The only evidence at our disposal bearing upon this particular aspect of the problem, is that gathered by the parties that have visited Cape Crozier during the winter and spring, and that provided by Amundsen.

At the former station, each party in turn has remarked upon the fact that, after any blizzard of normal strength, the sea north of Cape Crozier has been swept clear of ice to the horizon. Additional evidence of this being the normal state of affairs is, we think, provided by the fact that Cape Crozier is occupied by the only Emperor Penguin rookery known to exist in the Ross Sea. The desiderata for such a rookery are presumably three in number :—

(*a*) Shelter from the direct force of the wind.
(*b*) A reasonably safe site for the rookery itself.
(*c*) Access to open water for feeding purposes throughout the year.

* This winter was, however, an exceptionally stormy one.

Of these three, the last two only affect the present problem. As regards the site for the rookery, sufficiently large pieces of Fast-Ice may be expected to form in any position where the coast has shallow indentations such as that formed by the junction with the Ross Barrier, and where the steeper portions of the coast and barrier form a wind-break. Access to open water, other than the hazardous expedient of having recourse to problematical and easily-closed cracks, is essential for the proper rearing of young ones born in the middle of the winter. The only other Emperor Penguin rookery known—that at Queen Mary's Land—is within easy reach of open water.*

Professor David, who met Amundsen immediately on his return from the Antarctic, has placed it on record that, during the whole of the winter at the Bay of Whales, open water was never out of sight of the Norwegian winter quarters.†

Thus, the evidence from this station confirms that already cited from Cape Crozier. Further evidence in the same sense is provided by the way in which the sea remained open north of Cape Royds during the Shackleton Expedition, 1907–9, and also at the entrance to McMurdo Sound during the Scott Expedition, 1910–13, and particularly in 1912. Every blizzard of any force was able to carry out of sight what coastal Fast-Ice it was able to break away. Almost certainly, therefore, in a normal season, it may be taken for granted that the Ross Sea is not normally held in the grip of a sheet of Fast-Ice of any thickness. The little evidence that has been collected rather tends to suggest that large areas are not frozen at all at any time during the winter. In a stormy season, this is probably not true to such an extent, as the relays of ice broken away from the coastal strips of Fast-Ice must go far to fill up even a great sea such as this, while the passage of the main pack in a westerly direction across the mouth of the sea will surely stop the northward drive which might otherwise prevent such a segregation. Should such an accumulation of pack take place, there is so much the more likelihood of the interstices between the fragments of the mosaic freezing. It is a paradox, but quite a reasonable one, to imagine the Ross Sea filled with ice-floes cemented by local ice in a stormy season with a high mean air temperature, but comparatively free either from derived ice or ice formed *in situ* in a calm, cold winter.

In the same way, it is to the continual presence of a comparatively close medley of Pack-Ice in the North Polar basin that we must quite likely turn for an explanation of why that sea is always so ready to freeze over in a calm spell.

The problem is not soluble with the information at present available. It is worth investigation, for it may have a very practical bearing on the fortunes of a ship in danger of being beset during the late autumn or early winter. A bold drive into the centre

* Stenhouse, the captain of the "Aurora" in the recent Shackleton Expedition, has reported seeing an old nesting-site for a dozen or so birds within the pack in which he was beset in 1915. He speaks of this as a "rookery," but specifically states that he saw no birds, but only the evidence of the floe having been used as a nesting-site. The floe with the remains was seen in November, 1915; but, having regard to the known habits of the Emperor Penguin, it appears much more likely that the floe was one which had been broken away comparatively early in the winter from Cape Crozier. If this is so, it affords another interesting piece of evidence of the westerly drift.

† David and Priestley, 'Shackleton Geological Memoir,' vol. 1.

of the Ross Sea might well, in a favourable season, gain a freedom which would be unobtainable by keeping along the coast.

The consideration of the Ross Sea pack would not be complete without some reference to conditions to the east of the sea. Here, off King Edward VII Land, there seems to be an area where pack of unusual thickness and age is formed. The "Discovery," when it penetrated far east of where any ship has navigated before or since, reported apparent shoals studded with ice-islands (?), or bergs, which acted as a nucleus for an accumulation of Fast-Ice of a thickness not met elsewhere in this area. Nothing seems more likely than that such cause and effect should actually exist. A similar sequence of events has led to an accumulation of similar type, and even greater dimensions off Kaiser Wilhelm Land, as reported by von Drygalski under the name *West-Eis*. The breaking away of the edges, and, in particularly stormy years, of the main portion of this perennial accumulation, would suffice to account for much of the unusually heavy element in the pack at the entrance to the Ross Sea.

In the passage made by the "Terra Nova" through the pack in 1910, an exceptional amount of such heavy ice was seen. Captain Scott describes a particular strip as follows :

> "We first got among the very thick floes at 1 a.m., and jammed through some of the most monstrous I have ever seen. The pressure ridges rose 24 feet above the surface—the ice must have extended at least 30 feet below."*

Amongst these floes were some, quite unridged, standing 8 to 10 feet out of the water. Nothing comparable to this has been seen in the Ross Sea, except perhaps the three- or four-year-old Fast-Ice at the back of McMurdo Sound, or the portions of the Ross Barrier where lowest.

Part of the accumulation is doubtless due to the fact that the snowfall is heavier in the region where the floes formed, but one cannot escape the conclusion that this ice was the accumulation of at least two or three seasons.

Life-History of Pack-Ice in Detail.

(*i*) *Definitions.*—The elements of which the Ross Sea pack met in 1911 were composed have been defined by Captain Scott as follows :—

(1) "The ice which has formed over the sea on the fringe of the Antarctic Continent during the last winter.

(2) "Very heavy old ice-floes, which have broken out of bays and inlets during the previous summer, but have not had time to get north before the winter set in.

(3) "Comparatively heavy ice formed over the Ross Sea early in the last winter.

(4) "Comparatively thin ice which has formed over parts of the Ross Sea in the middle or towards the end of the last winter."

To these must, of course, be added bergs and the occasional floes several years old to which reference has just been made.

* Scott's Last Expedition, Vol. I.

In order to define and describe such a heterogeneous collection, certain standard types must be selected and given names.

This is necessary both for individual pieces of ice, for areas of pack consolidated as a whole, and for the waterholes which seam the pack, the presence or absence of which is so important from the navigator's point of view.

Such a series of definitions has already been evolved for the pack of the North Polar Sea, whose study was commenced almost in Elizabethan times. A certain looseness of application of these terms and misconceptions as to their original meaning has, however, resulted in much wrong description of ice.

It is, therefore, considered advisable to repeat at length the list of definitions carefully compiled from the study of the original authorities by J. M. Wordie and revised with him by the present writers.

Sea Ice Definitions.

Slush or Sludge.—The initial stages in the freezing of sea water when it is of gluey or soupy consistency. The term is also occasionally used for " brash-ice " still further broken down.

Pancake-Ice.—Small floes of new ice approximately circular and with raised rims (Plate CCXLIX).

Level-Ice.—All unhummocked ice, no matter of what age or thickness, which has platy structure and fibrous appearance when broken (Plates CCL and CCLI).*

Fast-Ice.—Sea ice while remaining fast in the position of growth. True Fast-Ice is only met along coasts where it is attached to the shore, or over shoals where it may be held in position by islands or stranded ice bergs.

Pack-Ice.—Sea-Ice which has drifted from its original position.

A Floe.—An area of ice, other than Fast-Ice, whose limits are within sight. Floes up to 2 feet in thickness may, for convenience of description, be termed " light floes " ; floes thicker than this, " heavy floes."

A Field.—An area of Pack-Ice of such extent that its limits cannot be seen from a ship's masthead (Plate CCLII).

A Crack.—Any fracture or rift in sea ice (Plate CCLIII).

A Lead or Lane.—A navigable passage through Pack-Ice (Plate CCLIV).

A Pool.—Any enclosed water-area in the pack, other than a crack or a lead or lane (Plate CCLV).

Frost Smoke.—The foglike clouds which appear over newly-formed water areas in the pack, owing to the consequent supersaturation of the lower strata of air with water vapour.

Water-Sky.—Dark streaks on the sky due to the reflection of water spaces, or the open sea, in the neighbourhood of large areas of sea ice.

Ice-Blink.—The white or yellowish-white glare on the sky produced by the reflection of large areas of sea-ice. (The antithesis of water-sky.)

* Called "Young-Ice" by Wordie.

Hummocking.—The result of pressure upon sea ice (Plate CCLVI).

Hummocky-Floes.—Floes composed wholly or partly of re-cemented pressure ice.

The Pack.—The term used to denote the main belt of derived ice which, in the Antarctic, girdles the continent south of the zone of the " Westerlies " and, in the Arctic, fills the Polar Sea and escapes southward from the outlets of the sea. (French : *Banquise de dérive.*) The term "pack" is used more generally to mean any area of Pack-Ice, however small.

Close Pack.—Pack composed of floes mainly in contact (Plate CCLVII).

Open Pack.—The floes for the most part do not touch (Plate CCLVIII).

Drift Ice.—Loose, very open pack, where water preponderates over ice (Plate CCLIX).

Brash.—Small fragments and rounded nodules; the wreck of other kinds of ice (Plates CCLX and CCLXI).

Bergy Bits.—Medium-sized pieces of glacier ice, or of heavy floes, or hummocky-pack washed clear of snow. (Typical " bergy bits " have been described as "about the size of a cottage.")

Growlers.—Similar pieces of ice to the above, but so small as barely to show above sea-level (Plate CCLXII).

Rotten-Ice.—Floes which have become much honeycombed in the course of melting, or which appear black through saturation with sea water (Plate CCLXIII). (Thin sheets of newly-formed very thin ice also appear black, and may easily be confused with the last type when met in the pack.)

The above list is substantially the same as that given by Wordie in his paper, though in some cases the wording has been somewhat altered. The single exception of note is the substitution of " Level-Ice " for his term " young ice."

At the time of the original discussion of the terms, exception was taken to the application of this name to areas of flat ice of whatever age. The older floes of this type are adequately described by the name " bay-ice," given to them by David and Priestley in the Shackleton Expedition, 1907–9. It is unfortunate that a prior use of the term for ice formed in openings of the pack (which are usually entirely different in form from " bays " as geographically defined) prevents its more legitimate application to ice formed in real bays, and therefore likely to survive to an age greater than normal. Since some name is required for the level pans which form quite a significant proportion of the pack at any one time, the present writers have determined to propose the term " Level-Ice." This name has the merit of emphasising the one characteristic which differentiates these floes, whatever their origin, from the Hummocky-Ice with which they are in sharp contrast. Normally they consist of a band of greater or less thickness —usually an inch or so only—of horizontally-lying plate-like crystals, followed by a generally vertical arrangement of crystals throughout the remaining mass of the ice. The appearance has been well expressed in the term fibrous ice, frequently applied to this type.

There is, however, good reason for avoiding this name as the designation of the class. In the upper portion of the older floes, this structure has frequently been converted

by molecular re-arrangement into an interlocking granular structure reminiscent of the ice of glaciers. A spotty appearance is then given to the ice by the aggregation of the air-content into definite bubbles between or within the crystals. This change will take place at any temperature, but only proceeds quickly at temperatures well above zero, where melting takes place to some degree. It is facilitated by the removal of the ice-blocks from the water, but will apparently take place in the central upper portion of a large and thick floe still immersed in sea water. It is accompanied by the draining of salt from the blocks already described elsewhere.

The process has a practical application, for it is to such elevated old floes that the ships' companies turn for the renewal of their fresh-water supply when navigating in the pack.

The life-history of sea ice in the pack differs little from that already described in Chapter X with reference to Fast-Ice. Indeed, the only differences are in the degree in which the various factors which cause its formation, modification and dissolution act. As might be expected in a moving field of ice-floes, driven hither and thither by the wind and buffeted at either edge by the waves, those changes which are produced by pressure take place in by far the greatest degree. The dominant impression left on the mind of the observer by any particular area of pack is the amount of what David has referred to under the name "screwed pack," but which is perhaps more correctly described as "Hummocky-Ice," a term which, while emphasising its characteristic appearance, refers only very generally to the processes which have brought about this result.

Even if exposed to the same forces, the movement of the various heterogeneous elements comprising the pack will be so different that pressure is bound to take place. The different shape of the individual floes, the difference in the surface area exposed to the influences of wind and current respectively, must ensure unequal movement even as between one floe and another. The equally certain difference in force of the agents making for movement at one and another part of the pack is another factor potent to produce hummocking. The interposal of immovable obstacles such as capes and ice-tongues in the way of the moving icefields is of paramount importance in producing pressure on a huge scale. The presence of icebergs of land ice many hundreds of feet thick produces pressure effects which are neither local nor slight.

The immediate effect of pressure of any description, except in the very youngest ice, is the formation of shear-cracks. Cracks from other causes are common in sea ice sheets, and one type of crack—the contraction crack due to temperature—has been dealt with earlier in the memoir under the heading "Fast-Ice." It suffices to say here that in the pack, as studied at the entrance of the Ross Sea, such cracks played a very subordinate part. This is doubtless due to the relative lack of cohesion amongst the elements of the ice. It is comparatively easy for temperature changes to be taken up by the opening of already existing water spaces.

In his exhaustive notes on the effects of pressure in the Weddell Sea Pack-Ice, J. M. Wordie has recognised three types of cracks directly due to pressure :—

(*a*) Weight or hinge-cracks.
(*b*) Shock- or concussion-cracks.
(*c*) Torsion-cracks.

At the entrance to the Ross Sea, cracks of both types (*a*) and (*b*) were observed to form on many occasions.

The piling up of the pressure ridge to the north of the Ridley Beach produced a crop of cracks of type (*a*) in front of it ; concussion-cracks, on the other hand, were formed whenever the pack from the main sea was piled up by the flowing tide against the sheet of Fast-Ice in the bay. Similar "weight-cracks" are well formed in Fast-Ice opposed to the face of an advancing glacier, when they are accompanied by shear-cracks of an entirely different nature. Perhaps the most notable cases of concussion-cracks on a small scale are those formed by the surging about of bergs through the close pack.

These titans have an effect closely analogous to that of the prow of an ice-breaker, and this is also seen on a less efficient scale in the case of our own wooden vessels.

Only one undoubted example of the formation of torsion-cracks on a large scale was noted by the Scott Expedition during the time the writers were on board the "Terra Nova." This was during the first voyage down, when a shift of wind was accompanied by the formation of typical chains of open waterholes, in pack composed for the most part of unusually large floes. Attention was particularly drawn to it, because of the possibility presented of making good progress south along the course thus opened up. On several other occasions, chains of undisturbed floes of black ice amidst much heavier pack suggested a similar effect dating from some time before the ship reached the latitude at which the floes were found. The screwing of large floes moving in one direction, by the application of a force from another, must always tend to open such spaces, which will remain clear only until the pack again closes under the new conditions.

One other type of crack recorded by Wordie from the Weddell Sea is that due to relief from strain brought about by unequal loading. This is undoubtedly a prime cause in preventing the solidification of the pack, and would act even if the latter were exposed to no other force tending towards disintegration. In the case of Fast-Ice it may act over comparatively large areas, as, for instance, in the case of the local snowfall along the west coast of Robertson Bay, and in the lee of any glacier cliff where snowdrifts tend to accumulate.

In the pack, however, its action is mainly from day to day and between floe and floe. The difference in equipoise which produces the cracks may itself be caused either by unequal accumulation of snow above or by unequal melting below. It is, in either

case, a potent factor operating against cohesion on a large scale. It must play a particularly important part along the edges of the pack, in helping the swell to bring about that final dissolution which so quickly resolves an almost impenetrable belt of ice into a haphazard collection of bergy bits, growlers and brash.

The relation between pressure and the resulting types of ice was best seen in the present Expedition at the seaward border of the sheets of Fast-Ice which were subjected from time to time to the irruption of the main pack circling the Ross Sea. They have therefore been described in detail in the chapter on Fast-Ice. Typical examples of small hummocky-floes seen in the Ross Sea pack are, however, figured in Plates CCLXIV and CCLXV, in the latter of which is also shown an excellent example of "rafting" due to the squeezing of a strip of Fast-Ice formed of loosely cemented squarish slabs (the initial stage in the formation of Pancake-Ice). In Plate CCXLVIII, a common phenomenon, the thickening of a floe from above by the addition of frozen sea water, is seen. When small floes of Level-Ice are converted into hummocky-floes, either by the upturning of their own border or by the addition of fragments from their neighbours, the consequent depression of the main surface below the water often has this result.

The height of the hummocky-floes and pressure ridges met in Arctic and Antarctic navigation has probably been more exaggerated by imaginative reports than any other single class of Polar statistics, except perhaps the height of bergs. It was unusual, in older days, to hear of pressure ridges less than 50 or 60 feet, or of bergs less than several hundreds of feet, high. The advance of science in the exploration of the polar lands and seas has gradually eliminated these outside estimates, and more moderate and accurate estimations and calculations are now the rule. The pressure ridges actually seen in formation in the neighbourhood of the winter quarters of the Scott Expedition nowhere exceeded 20 feet in height. Those met in the pack were unusually high, but nowhere more than 30 feet. This latter figure must, we think, be considered nearly a maximum for this sea of comparatively unchecked movement. It is possible that this height is somewhat exceeded against prominent points of the coast further to the north.

Subsequent Changes in the Structure and Content of the Ice.

The changes which take place in sea ice subsequent to its formation, but prior to its final dissolution, have already been discussed under the heading "Fast-Ice." There is one thing, however—the impregnation of the lower layers of sea ice with diatoms—discussion of which belongs more properly here. For many years it has been an observed fact that, in the summer, myriads of diatoms become entangled in the meshes of ice-sheets floating in the Antarctic seas, giving a brownish-yellow colour to the ice layers into which they penetrate. This is so usual an occurrence that the brown discoloured ice is of distinct use in distinguishing between ice one year, and ice less than one year, old. Beyond this the distinction cannot be relied upon, since sea ice of two or three

years of age is not likely to show more than one band of diatomaceous ice. The limit to which the diatoms penetrate is the upward edge of the water-soaked ice in the summer. As a general rule, this will be very near sea level.

At any rate, in a two-year-old floe it is likely to be higher than the lower limit of the diatom-bearing ice of the first year. Fast-Ice frozen in the bays of the Ross Sea does not appear to have diatom-laden bands at all. The presence of the diatoms in Pack-Ice has an interesting bearing upon the movement of the surface water of the pack-belt. Drygalski has pointed out that the deposits on the bottom of the sea, under the pack in which the "Gauss" wintered, were remarkably free from diatoms, though the ice itself was heavily diatom-laden. The fact appears to have been confirmed by subsequent explorers operating within the Antarctic pack-belt.

Some explanation is obviously required to account for these facts. Drygalski himself has postulated an outward surface current of the "melt-water" from the pack, together with a consequent upward movement of the water layers beneath the pack, to take the place of the water thus distributed. Such an upward current would to a great extent neutralise the gravitational descent of the microscopic carapaces of the dead diatoms and the organisms which prey upon them, and would tend to the concentration of these siliceous remains north of the pack-belt. Such a concentration does apparently take place.

A similar concentration on a lesser scale must presumably exist to the south of the pack-belt also, since here also much melting takes place in the summer. Here, however, little is known of the bottom deposits, and, in any case, such a deposit might well be masked in the greater amount of glacier, thaw-stream, wind and pack-borne terrigenous material.

Evidence from an entirely different source would seem to bear out Drygalski's contention. Both to the north and the south of the pack there is a separation of the smaller sea-worn fragments—drift-ice—which make up the outer belts where the ice is continually being worn down by the swell. This takes place to an extent which is difficult to account for on any other supposition than an outward current such as Drygalski postulates. The actual occurrence of such a current should be easy to demonstrate if any ship has the time to spend on a systematic investigation. A comparison of salinities of water samples should also yield interesting results. During the phase of Antarctic exploration directly associated with the unveiling of the interior of the continent, involving as it does lengthy stays on Antarctic shores, with the necessary establishment of winter quarters, such detailed examination of the pack and its environment has not been feasible. Such results as have been obtained have been incidental to otherwise unwelcome detentions.

Disappearance of Ice.

The causes of the disintegration and dissolution of sea ice have also been dealt with at some length in the chapter on Fast-Ice. In the case of Pack-Ice, the same factors

operate, though in somewhat different proportion. For instance, it will be quite clear that the *rôle* played by melting on the upper surface will be decreased in proportion as the ice is free from wind-blown sand and dust, and is more uniformly covered with a pure white snow covering which reflects a large proportion of the rays of the sun which fall upon it.

Surface pools are very uncommon upon the surface of ice-floes in the main pack. In fact, pools such as are described as a common feature of the Arctic pack are unknown to the writers, except upon the summit of icebergs, or along the Fast-Ice strips near a coastline. Dissolution of the under surface is, however, as might be expected, proportionately greater in the latitudes to which the pack is driven by the southerly gales. The body of comparatively warm water at the southern edge of the westerlies must provide a continual (relatively) warm bath for the northern edge of the whole Antarctic pack. Indeed, the efficiency with which the sea water melts the pack as quickly as it is carried forward by the southerlies is a factor which assists to prevent the invasion of the southern shipping routes by dangerous and even impenetrable fields of ice.

The swell, on the other hand, plays a less important part than it does in breaking up the more stubborn Fast-Ice of the indentations of the coast further to the south. The mechanical attrition of the floes must result in the formation of a quantity of brash, but the breaking up actually accomplished by the swell is confined to the comparatively few survivors of the large floes, most of which have already been split, shattered and pulverised in the stormy passage from the latitudes where they were originally formed.

Perhaps the most striking of the phenomena accompanying the dissolution of Pack-Ice, is the formation of the knob-like or cup-like forms carried on broader submarine bases, examples of which are figured in Plate CCLXXXII, and which have been appropriately named "Swan-Ice." They mark a distinct step in the breakdown of floes and bergs, and occur in great numbers round the shores of the continent, particularly in March and April, the months when the more stubborn pieces of ice are just disappearing. They also occur commonly along the outer belt of swell-tossed Pack-Ice, the frequent entire submergence of the fragments being sufficient to account for a departure from the characteristic form.

Many of them show double heads, each raised on a separate neck, as figured in Plate CCLXXXII. It seems probable in such cases that the position of the cups bears a distinct relation to the period of vibration of the ice upon the swell, the laving by which has given the floe its characteristic form. The tendency to form a neck-like attenuation about sea-level is equally marked along the edges of the larger flatter homogeneous floes at a similar stage when melting is predominant. A similar effect is also frequently seen in water-worn bergs, the long submarine spurs thus formed being one of the dangers of navigation in ice-infested seas.

The formation of the neck is, of course, due to the greater efficiency of the surface layer of sea water as a melting agent than the layers beneath it and the air above. It is

only where the top layer of sea water is warmed above freezing-point by the sun that Swan-Ice can occur in its most pronounced form.

Navigation and Exploration on Pack-Ice.

The study of Pack-Ice in southern seas has naturally a very practical bearing upon navigation in the immediate neighbourhood of the Antarctic Continent. If the *terra incognita* of the Antarctic coasts is to be explored and surveyed from the sea, future navigators have a task before them far surpassing in difficulty that achieved by their predecessors.

The portions of the Antarctic Continent still unknown are those which have baffled the most intrepid sailors of the nineteenth and, so far, of the twentieth, century. Our present knowledge of the configuration of the coastline, together with the certainty of the main westerly drift of the pack, do, however, enable the problem to be attacked from the most favourable points.

For instance, it is clear that the exploration of the unknown portion of the Weddell Sea can only be undertaken by sea with any chance of success, by attempting, as Shackleton did, to run down the coast of Coats Land where the main pack-stream thins out after passing the eastern shores of the sea. So, also, the attempt at the survey of Enderby Land must be made from the direction of Queen Mary's Land.

The exploration of the Antarctic coastline, by travelling on the Fast-Ice and Pack-Ice along the coast from bases at convenient points on land or land ice, has long been the dream of many Antarctic explorers.

Past experience shows that the legitimate exploitation of strips of Fast-Ice in the spring and early summer may lead to considerable achievements in this direction. Arctic explorers have waxed scornful when comparing feats of this type accomplished in the Arctic with those in the Antarctic.

While admitting, however, that much may yet be done by this method, the writers would sound a note of warning against the tendency to apply Arctic methods to the Antarctic, regardless of Antarctic conditions and experiences.

In the North Polar basin, the pack moves steadily across or round a comparatively open, but entirely shorebound, sea. Its only outlets are a number of extremely narrow channels where contact with the shore is invariably made.

Travelling on Arctic pack without boats is a comparatively safe proposition. Journeys of 1,000 miles or more have been accomplished, even by quite ill-equipped parties such as the survivors from a crushed ship. In those regions where life abounds, and they appear to be many, good progress can be made, because the habit of living on the land, first used systematically by Stefanssen as an aid to geographical exploration, has done away with the necessity for dragging heavy burdens of food.

In the Antarctic, on the contrary, the conditions are essentially different. To begin with. the movement of the Antarctic pack is around and outwards from a central land mass towards the stormiest seas in the world, where melting takes place, and the

last hope of a marooned ship's party is—if they have boats—the chance of reaching one of the comparatively few sub-Antarctic islands.*

Even should the westerly drift push the ice on which a sledge party is adrift against a buttress of the main Antarctic coast, still this coast is bordered for hundreds of miles on end by almost inaccessible ice-cliffs. Should fortune permit an escape to shore again, the party would scarcely be better off, for they would, in all probability, be hundreds of miles from help, without means of making their whereabouts known, and on a coast absolutely cut off from any inhabited country. Altogether, the exploration of Antarctic coastlines by sledge parties travelling on sea ice, though an exceedingly useful accessory method, has very well-defined limitations to overpass which would probably lead to catastrophe.

* Such a party would, ninety-nine times out of a hundred, be quite helpless without boats. Under almost any imaginable conditions, death by drowning—or, still worse, through the attacks of the killer whales—would be inevitable.

CHAPTER XII.

ANTARCTIC ICEBERGS.

(*A*) *General.*

Undoubtedly, the Polar phenomenon which has most touched the imagination of sailors of all ages has been the "ice mountain" of the early navigators—the iceberg of modern nomenclature.

In these days, when steamships are almost universal, the significance of the iceberg to the crew of the sailing ship is difficult to realise, though modern disasters, such as the loss of the "Titanic" in 1911, serve to remind us that large masses of floating ice still constitute a menace to navigation. The Arctic icebergs were known and dreaded for centuries before those of the South Polar region were encountered, and the marked contrast between the majority of Arctic and Antarctic icebergs at once struck the early Antarctic navigators, who had nearly all had experience in Arctic waters, as being very remarkable. The whaling captains, Captain Cook, Sir James Ross—and, in fact, most of the early explorers of Antarctic seas—make special mention of the "tabular" icebergs of the south as being one of the most characteristic features of the region. It was not until a near approach to the shores of the continent was made that the cause of the particular shape of the largest Antarctic icebergs was realised. The discovery of the Ross Barrier in 1841, and of numerous other similar land ice-formations, at once explained the prevalence of this type of iceberg.

They were quite clearly the direct result of that particular stage of the glacial epoch which is associated with the overflow of the ice-sheets of the land into the sea, and with a climate and coastal snowfall which involved a sheathing of the continent in locally formed shore-ice.

The point which requires emphasising, however, is, that all round the shores of the continent, both where the shores are too steep and exposed to permit the accumulation of sheets of Piedmont-Ice, Confluent-Ice or Shelf-Ice, and too little dissected to allow a sufficient drainage from the Continental-Ice and Highland-Ice sheets to form Ice-Tongues, numerous steep cascading mountain glaciers of the type more familiar to northern eyes pour their quota of ice into the sea. At the snouts of such glaciers and of other glaciers of greater size in those regions of the coast with little local precipitation, typical icebergs of the more well-known Arctic types are formed in great numbers each year.

From these places, they are carried north and west along the coast to join the main pack, where, however, they are overshadowed and fade into relative insignificance beside the great tabular icebergs or "snowbergs," as they have somewhat incorrectly

been called. In actual numbers, it is probable that the variously-shaped glacier bergs would equal or surpass their more majestic neighbours, but the latter, with their clear-cut contours and their (often) immense size, are incomparably more striking to the eye, and must be responsible for the annual removal of a considerably greater amount of ice. Individually, the true glacier berg has perhaps the finer appearance, but nothing can be more impressive than the sight of a fleet of tabular ice monsters, often many miles in length, and averaging 50 to 100 feet in height, sailing majestically in a calm sea, churning up the pack as they move irresistibly northward in the grip of the Ross Sea current.

As regards the name "snowberg," which has sometimes been applied to these tabular bergs in the past, our own experience is that the term is a dangerous misnomer. Not one in fifty of the tabular icebergs seen during the present Expedition was of true nèvé. Almost all were formed of the cloudy bubbly ice of which the typical Piedmont-Ice Confluent-Ice and Ice-Tongues of the Ross Sea area are composed. This ice differs entirely from névé as figured and defined in the present memoir. It was only when true névé-bergs, or the type of iceberg we have named the "unconformity iceberg," which often had a capping of true névé, were met, that this became evident. From a distance, it is quite impossible to distinguish the two types, but the majority of tabular icebergs examined closely were found to consist of true ice, though most of it was stratified ice obviously derived from snow without the intervention of any pronounced melting.

The height of the icebergs seen during the Expedition varied from low bergs hardly distinguishable from floes of old Level-Ice, to bergs estimated to be 160 feet high.* The maximum height of the Ross Barrier was found to be 160 feet.

We may therefore estimate the height of the highest modern iceberg in the Ross Sea area as being somewhat less than 160 feet. By far the majority of those seen varied between the limits 40 and 120 feet—rather below the average height of the shore-cliffs of the Antarctic land ice formations. Many were less than this height, but these low icebergs were in a distinct minority, for ice-cliffs of less height than 40 feet are not common in the Ross Sea. The most notable exceptions are, of course, the low portions of the "rolls" of the Barrier, which are often nearly at sea level. The breaking away of such low portions gives rise to fleets of unusually low bergs, such as those met by the "Nimrod" in January, 1908. Another exception is due to the breaking away of sea ice laden with the accumulation of several years' snow—the early stages of what might have become Shelf-Ice of the King Oscar Land type. Yet another type of low iceberg, quite common in the Ross Sea, is the small berg consisting, for the most part, of greasy-looking and streaky-white ice which is formed by the calving of portions of the Antarctic icefoot.

The area of the greatest of the tabular icebergs almost surpasses belief, but the existence of single bergs up to 30 miles in length, many hundreds of miles from land, is now well authenticated. The "Challenger" Expedition, Sir James Ross, the

* The greatest height measured by the Scott Expedition was 140 feet.

"Nimrod" and the "Terra Nova" Expeditions, to mention only four cases, all observed icebergs between 20 and 30 miles long, which needed several hours' sailing or steaming to clear. Icebergs a mile or more in length occur in hundreds; and, indeed, the breaking away of ice in the Antarctic clearly takes place on a scale quite unknown elsewhere in the world. Mixed with these immense four-square bergs are thousands upon thousands of smaller ones of all sizes, of several types, in every stage of dissolution. In size they vary from the great leviathans already mentioned, through the lesser tabular bergs, to the greatest of the true glacier bergs, and thence again past the product of the cascading glaciers, to the small icefoot bergs, and, finally, the growlers, which represent the last clearly distinguishable products of land-ice. Beyond this stage, the "bergy bits" and "brash" derived from the denudation of icebergs are in no sense distinguishable—except in their intimate internal structure—from the similar results of the disintegration of sea ice.

The age of the Ross Sea iceberg varies greatly according to the incidents of its life-history. Even under what should at first sight appear to be the most favourable circumstances—for instance, when stranded on a shoal in high latitudes—dissolution proceeds at great speed during the summer months, and the disintegrating forces are often by no means idle during the winter months. Two quite distinct cases therefore require consideration in this connection. They are, respectively, the case of bergs detained in Antarctic waters and the more normal case of bergs which are carried straight into the pack and so north to the open sea.

Very many icebergs formed in high latitudes are likely to have some difficulty in reaching the main pack-belt, and this is probably more so in the case of the true glacier bergs than the tabular bergs, the ice of which has a less density. Striking examples of the contrast were seen at Cape Adare in 1911. The submarine extension of the beach on which Camp Ridley is built lay athwart the tidal current in and out of the bay. Daily the current on the ebb-tide brought its load of floes and bergs close past the point. It was most instructive to see low glacier bergs stranding comparatively far out, and tall, majestic tabular bergs sailing steadily past inside them. Not once, but on several occasions, did well-marked cases of this occur. Such a difference in draught must have a considerable effect in concentrating tabular bergs in the outer pack-belt and detaining icebergs of glacier type, until nearly the end of their career, in Antarctic waters. A good example of delay in the passage north of an iceberg was provided by part of Glacier Tongue, which stranded for several months at Cape Bernacchi before moving on elsewhere.

At every winter quarters established in the Ross Sea area, there have been at least several icebergs stranded, usually of true glacier ice, so that the study of their disintegration in high latitudes has been made easy.

The earliest stage in the dissolution of such an iceberg is usually the rapid rounding of its more angular contours by the comparatively warm waters of the autumn sea. This is accompanied by a certain amount of undermining and calving of relatively unstable portions, while lumps of sea ice are often thrown upon its top during this and

the next stage while the sea is still open (Plate CCXLI). As the winter temperatures set in, the iceberg is next covered by a thick coating of spray, which gives it a very characteristic appearance, and which may be so thick as materially to alter its equilibrium. This coating renders bergs whose history has included the "stranded" phase to be easily recognisable (Plate CCLXVI).

This stage of accumulation ceases with the final freezing in of the sea ice, and the passing winter is accompanied by a steady growth about sea level, often with the formation of a well-marked tidal platform (Plate CCLXVII). At the same time, solution may be taking place towards the base of the iceberg and some ablation in the upper portion exposed to the air, though it should be noted that the latter is not usually sufficient to remove all the spray ice which has been added to the berg in the autumn.

Changes of temperature meanwhile cause the formation of cracks which do not again cement, and hence render the berg peculiarly vulnerable to the assaults of the waves in the following summer (Plate CCLXVIII). In a tabular berg in which cubical jointing is well developed, the frost action may result in a complete crumbling of the upper portion of the berg. This is well seen in Plate CCLXIX, where the avalanching of the *débris* on the sea ice is proof positive that very considerable disintegration took place during the three months between the freezing over of the bay in which the berg was stranded and the visit made by the sledging party which took the photograph.

The above summary which is the result of the observation of many icebergs stranded near winter quarters, gives a good idea of the amount of destruction which can be achieved under these circumstances by the weathering agents during a single autumn and winter. Such a berg is usually sufficiently broken up to permit it to clear the shoal on which it has been stranded immediately the sea ice goes out in the beginning of the following summer. It then continues its journey to the pack as several much smaller fragments, and it is likely that a single season in the pack will carry these smaller bergs sufficiently far north to ensure their disintegration in the following summer. The life of an iceberg thus detained in the south is not likely to be more than three years, though, exceptionally, its detention south of the main ice-belt may be prolonged for another year or more.

The history of a tabular berg, or a glacier berg which reaches the main pack early in its first season, is for several reasons somewhat different. One characteristic of a broad belt of ice such as the ice pack is an absence of swell and waves, and this effectually limits the solvent action of sea water to the part of the berg at or below the surface, and also prevents any accumulation of sea-spray such as has just been described. At the same time, the more constant temperature of the air over the open sea reduces the cracking effect due to change of temperature. Similarly, the abrading action of the sea in the next summer is again diminished. The general result is seen in the more regular outline of bergs whose whole life has been spent in the ice pack. Such regular bergs are very common, and, in their case, disintegration is to a great

extent postponed until they pass through the outer streams of the ice pack into the open water to the north. Once this last step has been taken, dissolution must be relatively rapid, so that the age of the majority of Antarctic icebergs must be determined by the length of time spent in the pack. What this time is we cannot know with any certainty. A favourable association of winds and deep currents might conceivably keep the bergs within the ice belt for several years. What knowledge we have of the currents and winds of the Ross Sea area, however, suggests that bergs would receive few set-backs to their steady passage north while in the pack.

One noticeable feature of all icebergs seen in the Ross Sea pack has been their freedom from accumulations of snow. At first sight this might suggest that their stay in the pack has been short, but this fact is not to be relied upon as evidence. Owing to the comparatively small size of the majority of the bergs and the strength of the winds in the pack zone, accumulation of snow on the top of bergs is not to be expected to any great extent. Accumulations of snow in the neighbourhood of bergs will, of course, be continually broken up and carried away from the berg by the constant change in relative position of the pack elements. Another factor likely to prevent accumulation of snow on bergs in the Ross Sea area, is the relatively small precipitation, a point which has already been mentioned in another chapter.

The only apparent exception to the comparatively short life of Antarctic icebergs, is the case of bergs frozen in soon after they were formed over shoal-water and embedded in a sheet of Fast-Ice of more than ordinary persistence. The life of a glacier berg under these conditions is only limited by that of the sheet of Shelf-Ice of which it may conceivably come to form a part.

Such cases are exceptional, few examples of the inclusion of icebergs in such sheets having yet been recorded, though the *West-Eis* of von Drygalski appears to originate in some such way. If sheets of Shelf-Ice are formed from sea ice in this manner, however—and this seems to be conclusively proved—included bergs will quite likely have taken part in their formation, and, indeed, may have formed the "piles" which were the main strengthening elements of the original sea ice base on which the sheet has formed. Such bergs would become an integral part of the Shelf-Ice and would behave more or less in conformity with its other elements. They would then take part in the outward flow which would be the consequence of accumulation of snow above.

This may quite possibly be the explanation of some of the anomalies of structure seen in the face of ice-cliffs and icebergs which are not otherwise susceptible of explanation.

(*B*) *Life-History of Icebergs in Detail.*

The history of an iceberg, as apart from that of the formation from which it has been derived, commences with the operation of "calving." Calving may take place in several ways and for one of several reasons. Calving is the ultimate expression of the denudation of the seaward portion of Antarctic land ice formations, and is responsible for the delimitation of the seaward faces of all ice-sheets or streams which reach the sea.

Several notable examples of the calving of icebergs were observed on the present Expedition, from the calving of a "Barrier" berg from the Ross Barrier (Plate CCLXX), which threw spray and slush for many hundred yards, to the fall into the sea of isolated blocks of relatively small size from cascading mountain glaciers or from the seaward edge of Highland-Ice sheets sometimes ending far above sea level.

In the case of most importance—the formation of true tabular icebergs—the process may vary, from an almost infinitesimal downward and outward surge of the severed portion as a new crack opens far back in the Ross Barrier, to the complete submergence of the newly-formed iceberg with a consequent chaotic commotion of the waters into which it has fallen. The latter case is the more common, because the edge of such ice-sheets is usually in a state of unstable equilibrium owing to the undermining action of the surface waters of the sea. This melting action will go on without much visible effect, except in the corrugation of the lower layers of ice immediately above water and in the formation of caves. Sooner or later, however, the weight of the unstable portion of the sheet becomes too great and the edge scales off with a thunderous crash, the iceberg thus formed floating with a horizontal or slightly inclined top, according as the undermining action has been regular or irregular. It should be noted, however, that bergs formed in this way must usually have an inclined top, sloping downwards to what was the seaward side of the glacier.

Some other explanation is required to account for the formation of the great level bergs whose dimensions can often be measured in miles. The smaller bergs formed in this way and by true avalanche are often distinguishable from other icebergs, formed with less travail, by the occurrence upon them of blocks of sea ice. Accumulation of ice upon the tops of bergs is often, however, only an apparent phenomenon, the lumps being relics of weathering; true accumulation may also result from the charging of a berg against a glacier or Shelf-Ice face (Plate CCXCI).

True sea ice can occur on bergs through two causes. It may be flung on top of the berg, or the glacier from which the berg has calved, by waves; or it may be lifted up after a submergence such as has just been described. Beautiful examples, both of sea ice perched in this way, and of salt pools on a concave berg top have been seen in the present Expedition. Some such fragments are figured in Plate CCXLI of the chapter on "Fast-Ice." On more than one occasion, an iceberg of considerable size was seen to dip right under the sea when calving.

The formation of the great bergs, a mile or more in length or breadth, was never actually seen, though, at the front of the Sir George Newnes glacier and elsewhere, such icebergs were seen newly separated from the main sheet and only awaiting the breaking-up of the sea ice to enable them to float northward. Such horizontal-lying forms cannot be due in any great measure to undercutting. The chances are too great that their balance would be disturbed. Their formation is rather to be explained, normally, by the presence of great master-cracks, already existent in the ice-sheet from which they spring, and only requiring some slight readjustment of level or strain to re-open then and to cause a separation. That such cracks and crevasses are common

is well known. The action of the swell may be the determining factor in many instances, the slight rocking motion imparted to the seaward end of a sheet of Shelf-Ice being sufficient to upset a very unstable equilibrium.

Abnormally, there is little doubt that great fleets of such bergs might be set free by any catastrophe, such as an earth tremor, an explosive volcanic eruption, etc. Slight movements may still be going on along the main fault lines of the Ross Sea *senkungsfeld* and *horst*. Such movements may well have accounted for the greater part of the 30-mile recession of the Ross Barrier since 1841. Some such catastrophic action provides the most satisfactory explanation of the fleets of bergs met by the "Nimrod," in 1908.

The calving of large bergs may easily be the result of the local configuration of the coastline. Passage over a shoal or bank lying parallel to a shore along which ice is accumulating may cause marked lines of weakness, which might not be closed up under Antarctic sea-level climatic conditions. Before such a shoal, a local bay might well be expected in the face of the glacier.

Another place where such lines of weakness would exist is at the junction of a relatively stagnant with a relatively quickly-moving ice-sheet. Along these planes of weakness, the sea would work with greater effect, and such deep cuts as Relief Inlet and the Bay of Whales may well be caused by the enlargement of originally narrow strain-cracks by relatively quick calving of icebergs.

When once formed, the berg moves away from the parent field. Its form may be modified before getting clear, by the destruction caused by scraping along or butting into the main ice-cliff; but, sooner or later, it will draw away, and from that time the sea will become the main sculpturing agent.

The first important change in form will be the development of the submarine "spur," a ram-shaped protrusion below sea level which is very characteristic of almost all the bergs seen in the pack and which, incidentally, adds considerably to the dangers of navigation. Spurs are formed in tabular and glacier bergs alike. They will be formed quicker and to a larger size in the former, since the action of "overcutting" facilitated by the jointing of the tabular berg assists the action of sea water, which is common to both types. The main cause of the spur in bergs is the greater melting power of the warm surface layers of sea water. Erosion, both mechanical and physical, takes place most rapidly at and about sea level, and a prominent "neck" is the result. The neck, again, in the later stages of the weathering of the berg, gives rise to "undercutting" of the portion of the berg above sea-level, thus accentuating the spur. Illustrations showing submarine spurs (Plate CCLXXI), undercutting (Plates CCLXXII and CCLXXIII) and a combination of the two (Plate CCLXXIV) are shown. The break-up of a tabular berg, by what may be called "overcutting" along joints, is well shown in Plate CCLXXIX, which also shows very well, on the tilted surface of the berg, the perfection of jointing which can sometimes be seen in true névé-bergs. Similar overcutting in snow-covered sea ice is shown in Fig. 166 of the chapter on "Fast-Ice."

A pronounced feature of the weathering of tabular icebergs, whether by atmospheric agencies or by sea water, is the change in colour from the original dazzling white to an

equally beautiful blue. This result may be brought about in different ways, but it is due in the main to internal change in the structure of the ice, which is usually dependent upon the presence of water. Constant washing by sea water, or the exposure to relatively warm temperatures in summer, are the principal causes. The net result is increase in the size of grain of the ice and decrease in the air-content. The same process under different conditions has been noted and described as giving rise to blue-bands in glaciers.

Another phenomenon frequently associated with the denudation of icebergs of all types is the formation of caves, illustrations of which are shown in Plates CCLXXV and CCLXXVI. Such caves may also be formed in several ways. The commonest method perhaps is by the widening of vertical planes of weakness such as cracks, and horizontal planes such as bedding planes, by a mixture of mechanical erosion and solution. Another method quite common in bergs stranded in high latitudes is by the closing of the top of a crevasse by a deposit of frozen spray. Most bergs seen in the pack have caves at or near the waterline. Cases have been observed of fish caught up in the ice of bergs. Such occurrences are proof positive that, since the formation of the berg, it has received some addition—probably from frozen sea water. During the passage through the pack in 1910, a fish was thrown out upon one floe by the sudden upturning of another under the impact of the nose of the ship. Many times, seaweed and sea animals have been observed to be thrown up on the icefoot in storms, and frozen to steep ice slopes before they had time to fall or be washed back. Such cases could, of course, only occur at low temperatures, but instances frequently arise when stranded bergs are washed with sea spray at a temperature 40° or more below zero Fahrenheit.

There are, of course, other ways in which fish might be trapped in water pools in icebergs and subsequently incorporated in the main mass of the berg through freezing. At Cape Adare it was quite common to see small fish playing about in the surface water near bergs, sometimes right within undercut caves whose floor was below sea level. A sudden change in equipoise resulting in the tilting of the berg would suffice to cut off a considerable quantity of sea water and trap the fish. Debenham's explanation* of the mode of formation of the deposits of organic remains, so frequently found at the surface of glaciers, would also account for the presence of remains of fish in icebergs at the time of their separation from the parent mass.

Jointing and planes of stratification must often play a decisive part in assisting the quick weathering of icebergs. Cases have been met where the whole top 10 or 20 feet of a tilted stratified berg has slid off bodily into the sea, the split taking place along a bedding plane where for some reason cementation has been less perfect (Plate CCLXXVII). The possibility of such a thing happening is suggested by the ease with which snow sometimes breaks along the junction between two successive drifts. The quick deposit of soft snow-drift upon a very hard polished surface must constitute a line of weakness in a stratified ice-mass for many years after its consolidation. Unusually soft layers of snow must also at times act like layers of shale in rock complexes.

* *Loc. cit.*

Other cases have been seen in which such a slide has not been quite complete, leaving cubical remnants standing up like the "buttes" or monadnocks standing out from an otherwise peneplaned horizontally-bedded country (Fig. 171; Plate CCLXXVIII). Such isolated remnants are easily mistaken for sea-ice blocks at a distance.

The effect of jointing and crevassing on the weathering of icebergs is well seen in Plate CCLXXIX. Any such lines of weakness will provide an excellent point of entry for the tools of all the degrading forces. The rocking of the berg on a swell will tend to shake out blocks. The waves of the sea will find so much more surface on which to work both by solution and mechanically. The innumerable shocks experienced by the berg in passing through close pack will have more planes along which they can take effect. The stranding of a much seraced, jointed, or crevassed berg on a shoal may well cause its utter ruin and dissolution into a number of smaller pieces. Instances have been seen of a berg running ashore at a speed of 3 or 4 knots, and of the seracs on its upper surface collapsing as the upperworks of a sailing-ship have often done in similar circumstances.

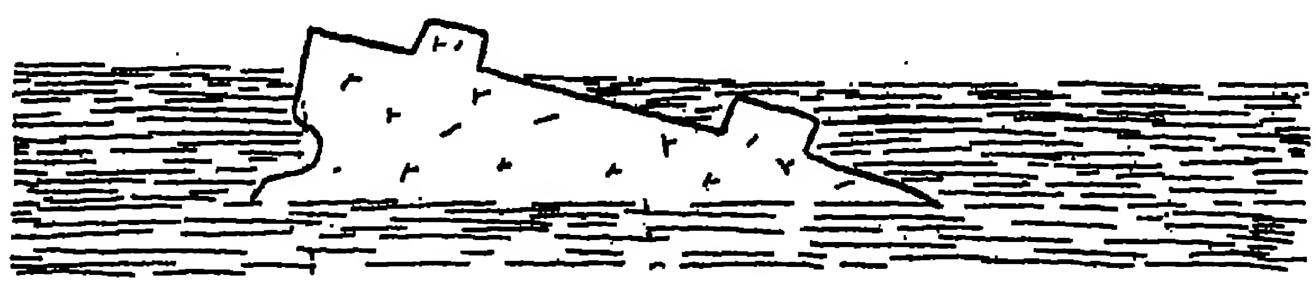


Fig. 171.—Tilted berg with monadnocks.

Examples of sudden breaking-up from apparently quite inadequate causes have been observed, but in such cases the cause must be looked for in the solution of the submerged portions of the berg, which may, under certain circumstances, go on much more quickly than weathering above the water level. One of the most dangerous features about an iceberg, when a near neighbour to a ship, is that nothing certain can be known about the state of the submerged portion, and therefore of the stability of the whole berg. Sudden submarine calving, with consequent overturning, is a well-known feature of all the later stages in the iceberg's history. Many of the nondescript blue-ice bergs seen owe their apparent anomalous shapes to complete overturning, a fact which can often be deduced from the disposition of the original stratification or dirtbands.

The geological work of icebergs during their short life is significant in several ways. As a distributor of rock, the iceberg is certainly of more importance than sea ice. The apparent virgin purity of the normal Antarctic iceberg is belied by the appearance of many of the tilted and overturned bergs in the later stage of decay. Such bergs are found frequently to contain considerable quantities of rock material. Even the apparently white tabular bergs when reduced in size by thaw and ablation often prove to contain a not inconsiderable amount of foreign matter. Good examples have been observed of icebergs stranded along the coast, from the upper layers of which dust and gravel have been concentrated until rock-drifts an inch or more in thickness have been formed. This, and the heavier material carried lower down in the ice, are all dropped on the sea bottom, and, at the present stage of Antarctic glacierisation, must form no

inconsiderable proportion of the bottom deposits. Much of the material dredged from the floor of Antarctic seas consists of rounded and ice-worn stones which must have been deposited in this way. A notable example, of particular interest because of its geological significance, is that of the haul of Cambrian limestone boulders brought up by the "Scotia's" dredge off Coats Land. By far the greatest part of our knowledge of the Antarctic Cambrian fauna has come from an examination of these rocks.

Another less important work carried out by icebergs is that which results from their frequent stranding upon shoals. At certain points along the coast of South Victoria Land this is well shown, and particularly so at Cape Adare. Here the tide runs twice a day past the end of the Ridley Beach. Icebergs are continually stranding on and bumping over the shoal, and the bergs keep this portion of the sea bottom completely free from life, while they must considerably alter the contour of the bottom, both by gouging and by carrying off pebbles with them when they resume their journey at a later date. The effect of bergs charging glaciers and sea ice is obvious. Both to the charged and the charger the result is disastrous, and such incidents are so frequent that they must play quite a noticeable part in preventing a greater accumulation of ice around the Antarctic continent. Icebergs in pack move always at a different rate from the other constituents of the pack. Wind has less effect upon them, so that normally they move more slowly. The pack in rear of them therefore surges past under the urge of the wind, giving rise to the curious optical delusion that the bergs themselves are moving in the opposite direction.* The presence of heaped-up pressure to windward and open lanes to leeward of a berg is a common phenomenon in the pack. The reverse process is seen when the wind changes and blows from a different quarter. Then the current in the lower layers of the sea still causes the bergs to move forward in the old direction, after the direction of movement of the surface water and the sea ice has changed. A similar contrary effect may be seen frequently when, as often happens, bergs are moving in a different direction from the Pack-Ice owing to the presence of a deep-water current. It is under such circumstances that they naturally perform the greatest amount of destructive work, and it is then that they are most dangerous to ships.

The later stages in the dissolution of icebergs, usually in the summer after their formation, is marked by the formation of smooth water-shaped contours, which are shown in Plate CCLXXX. This stage is marked by the occasional complete submergence of the berg during storms, and by frequent changes of equilibrium. Before this stage is reached, however, it may happen that, in a tabular berg, where the natural lines of weakness are most prominent, denudation may take place rapidly above water, while there still remains a broad stable pedestal below. In such cases, iceberg "swan-ice" may be very well developed, as shown in Plates CCLXXXI—CCLXXXIII. An illustration of another peculiar form, etched by solution and complicated by the deposition of the frozen spray of a second autumn, is illustrated in Plate CCXVIII.

* The distribution of bergs in the Ross Sea is not the same as that of the pack. At all times in the summer and autumn months bergs are found to the northward of the Pack-Ice. They are common throughout the pack, and to the south of it. On the last homeward journey of the "Terra Nova" a veritable fleet of bergs was met in March, well north of the usual position of the Pack-Ice.

Such rounded contours as are found in all sea-worn bergs are in marked contrast to the sharp outlines common on the seaward faces of glaciers. This contrast, of course, is a result of the difference between the part played by water in the weathering of the former and of the latter. Even on bergs stranded in high latitudes, thaw-water has much more effect than on neighbouring glacier cliffs. This may partly be attributed to the fact that the surface of all such bergs is coated to some extent with salt ice. The brine produced from the thawing of this must greatly assist in its turn to hasten the thawing of the salt-free ice beneath. In a similar way, the first signs of melting about a winter quarters occur either in drifts strewn with rock fragments and full of dust, or in the salty ice of the icefoot and Fast-Ice.

The effect of surf and breaking waves in disintegrating bergs is much assisted by the presence of the caves formed earlier in their career. This could particularly well be seen where the caves had been so numerous as to occupy a relatively large proportion of the iceberg's waterline. In such cases, it was quite common for the surf to batter its way right through to the surface of the berg, with the formation of great blowholes through which spray was thrown many feet into the air. The next stage would be the breaking away of large pieces of the roof of the cave, with the formation of "bergy bits" and "growlers," which are the penultimate product of the disintegration of land ice at sea.

(*C*) *Types of Iceberg.*

For the easy identification and description of icebergs, some division into types appears necessary. In the chapters on land ice formations, photographs will be found of the principal types of ice-sheets and ice-streams which give rise to bergs.

Other bergs may arise from the break-up of the Antarctic icefoot and of sea ice several years old with a heavy snow covering.

The present writers suggest the division of the bergs found in the Antarctic into the following classes :—

(1) *Icebergs with predominant angular contours.*
- (*a*) Tabular icebergs.
- (*b*) Glacier icebergs.
- (*c*) Unconformity icebergs.
- (*d*) Ice islands.
- (*e*) Névé-bergs.

(2) *Icebergs with predominant rounded contours.*
- (*a*) Weathered icebergs.
- (*b*) Bergy bits.

The first group of types—icebergs with predominant angular contours—includes all freshly-formed icebergs, except perhaps some of the small ones derived from icefoot or cascade glaciers, which would almost at once come under the heading "bergy bits" or "growlers." The second group—icebergs with predominant rounded contours—includes naturally all the older bergs which have been so much altered by the denuding

influences that their original form is indistinguishable. The criteria discriminating between the two main groups are not so much the straightness, or lack of straightness, of the approximately horizontal line bounding the upper surface of the berg, as the sharpness of its corners and the verticality of its sea walls.

The subdivisions of class (1) require to be defined and described more particularly, and an attempt to combine this with illustration follows :—

(1*a*) *Tabular Icebergs.*—The characteristics of the true tabular berg of the Antarctic are :—

(*a*) The great size which it sometimes attains, which is not approached by any other form of berg.

(*b*) Its rectangular, frequently very perfect, block cleavage, which is only found elsewhere in the névé-berg. (Often a somewhat conchoidal cleavage is marked in those formed of very homogeneous, rather compact, ice.)

(*c*) Its relatively large air-content, which is, however, concentrated within the granules and not more freely dispersed between a looser network of ice granules, as in névé.

(*d*) Its white colour and lustre, making the bergs appear at a distance as if formed of plaster of paris.

Such bergs are the derivatives of some forms of Shelf-Ice, Piedmont-Ice, Confluent-Ice, and Ice-Tongues, if the latter have had the upper portion above sea level formed from stratified layers of snow since converted into true ice. An essential of the tabular berg seems to be that the portion above sea level which gives the tabular form to the berg shall not have moved down from high land through the medium of a valley glacier. They are the most striking type of Antarctic iceberg, and are illustrated in Plate CCLXXXIV.

(1*b*) *Glacier Icebergs.*—The glacier iceberg is characterised usually by a more irregular surface, often broken up by crevasses into seracs, or lined with less important cracks It has usually a greenish tint, but may appear dazzling white under certain conditions of light. It is usually of more irregular shape and smaller than the true tabular iceberg, and is the equivalent of the Arctic type of iceberg which does not, however, appear to reach the dimensions sometimes attained by its Antarctic *confrère.* The cleavage of the ice is usually also irregular, and bergs of this type, unless formed of much crevassed ice, are usually much more resistant to weathering. Glacier icebergs are figured in Plates CCLXXXV and CCLXXXVI. They are derived from Ice-Tongues, Piedmont-Ice, Confluent-Ice, &c., which have not received a significant addition by snowfall at low levels, or from glaciers which do not extend into the sea. Icebergs from the latter source are of course much smaller than those from the former, but neither type is often seen of very great size, a quarter of a mile or so being usually the maximum length to separate off without breaking up further.

The few exceptions are derived from Ice-Tongues nourished rapidly from inland gathering grounds, in a region where coastal snowfall is small enough to be effectively neutralised by ablation, wind-chiselling and thaw.

(1*c*) *Unconformity Icebergs.*—This class of iceberg is a transition stage between (1*a*) and (1*b*) or (1*b*) and (1*e*), but it is so easily recognisable and occurs so frequently along the coast of South Victoria Land as to be worthy of consideration as a type by itself. Figs. 172 and 173 are diagrammatic drawings after photographs which were too poor for reproduction. They show two different bergs seen in Robertson Bay, which form good examples of this type. The origin of icebergs and ice-faces of this type has already been referred to in Chapter VII. Their characteristics are the well-marked unconformities below which the ice is of distinctly different type to that above. The difference may be very marked in degree, as between blue water-formed ice and névé, or less marked so that it is not easily distinguishable, unless shown up by the unconformable disposition of silt-bands.

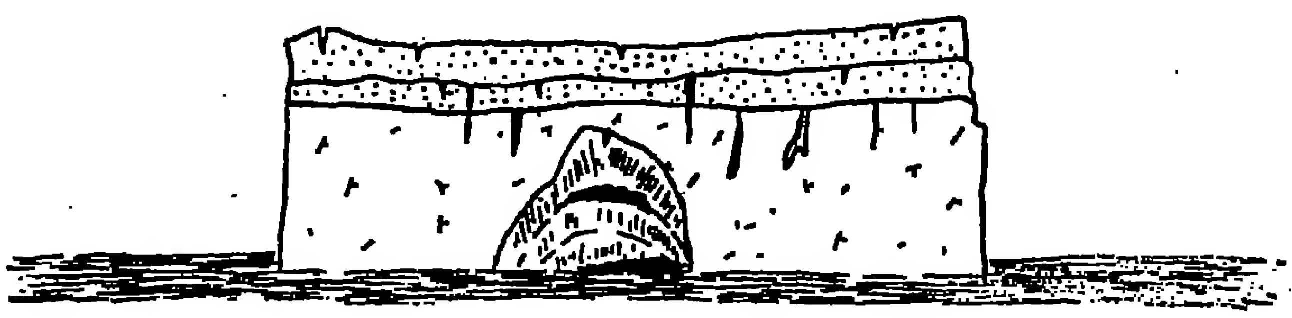


Fig. 172.—Unconformity berg with two unconformities.

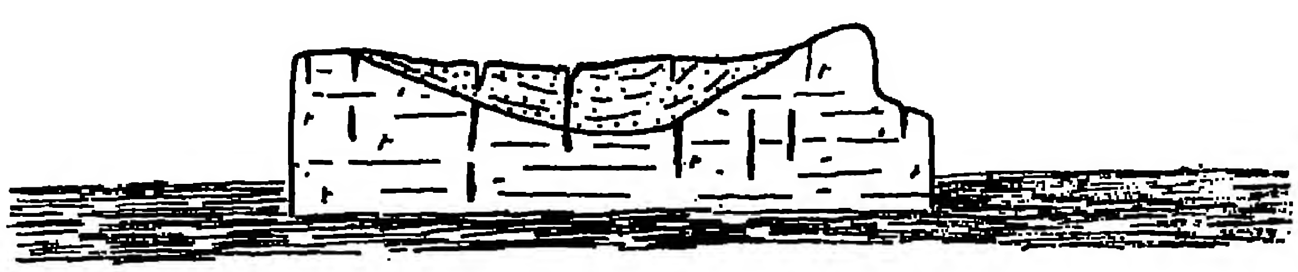


Fig. 173.—Unconformity berg. Structure shown up by silt-bands.

The more marked planes of discontinuity imply the lapse of considerable time between the formation of the upper layers of the older ice and the deposition of the new snow-drift upon the denuded surface.

Unconformity bergs may be traversed by two or more series of crevasses, one series stopping short at each old surface, and the youngest possibly traversing only the most recent ice-layer, possibly traversing all three. Such bergs are often unusually full of rock dust which has been concentrated along the unconformities. Such a concentration may imply the denudation of a considerable thickness of ice before the new phase of deposition set in. The less marked unconformities may be due to false-bedding caused by gusty winds, or to a relative change in wind direction causing a new lee and a scooping out of the drifts formerly deposited.

(1*d*) *Ice Island Bergs.*—One type of iceberg which, because of its shape, has received more attention from explorers than it intrinsically merits, is the ice-island type, which is shown in Plate CCLXXXVII. These conical-shaped bergs and somewhat similar dome-shaped bergs are fairly common, and they have frequently been mistaken both for rock islands and islands covered with ice. In certain lights, any iceberg will show dark by contrast with the sky, or with other bergs in the direct sunlight, while the shape of the ice-island berg is often reminiscent of Island-Ice, and fairly so of an island landscape such as might be produced. for instance, by volcanic action.

At least two methods of origin of ice-islands may be recognised; the shape being in the one case original and in the other case secondary. Shelf-Ice of the Ross Barrier type is not absolutely level, but has its surface thrown into "rolls," usually as the after

effect of pressure, possibly sometimes as the result of differential melting below. In the troughs between such rolls, the surface of the Ross Barrier may approach or almost reach sea level. The same troughs are often natural lines of weakness, along which inlets of the sea form by solution and from which iceberg-formation frequently takes place. If we imagine such an iceberg formed by successive calving along two such rolls, we obtain the typical elongated dome shape, which is one variety of ice-island often seen and which strongly resembles a low convex capping of Island-Ice over a small island. Similar rolls occur in many ice-tongues, and here pressure waves of more pronounced character may give rise to much more pronounced changes of contour on the surface of the resulting bergs, some of which may be almost tent-shaped. The term ice-island is, however, only given to large icebergs in the form of low domes or cones, as, for example, the one shown in the illustration. A secondary ice-island may arise from an ordinary tabular iceberg by differential-melting. If melting takes place quicker from the edges as sometimes happens, the sides of a tabular berg tend to droop, thus giving the characteristic dome-like form. This method is, however, not likely to give rise to very pronounced domes, as, before this happens, adjustment by calving is likely to take place.

(1*e*) *Névé-bergs.*—True névé-bergs are not very often met in the Ross Sea area, since ice-formations consisting in great part of névé are not common. The upper portion of an unconformity berg may often consist of true névé, or even of snow. Several névé-bergs were, however, closely examined in the Robertson Bay area, where the snowfall appears in places considerably to exceed ablation, and on the west side of which drift-chiselling and even drift snow is non-existent, at any rate in such a year as 1911, where the gales were of normal strength on the east side of the bay. Such bergs must be far more common where the climate is less desert-like than in South Victoria Land.

The ideal condition for their formation would be temperatures as at present, but with heavy snowfall in the sea-coast area, conditions approximated to on the west coast of Robertson Bay, where névé-bergs were seen most often in the present Expedition.

Whether the bulk of the glaciers above sea level consist of névé or bubbly ice appears to depend entirely upon the time taken for the accumulation of the thickness concerned—usually from 50 to 150 feet. This is true, of course, only for ice formations formed near sea-level and in the temperatures at present prevailing in the Antarctic, where, certainly, water plays no part except in the formation of definite blue-bands.

The névé-berg (Plate CCLXXXVIII) has much the appearance of a tabular iceberg, but the material of which it is composed—at any rate, above sea level—is true névé with the air-content dispersed in the boundaries of loosely coherent ice grains, in size between one-eighth and one-quarter of an inch in diameter, or smaller. The specific gravity of the berg is comparatively small, as was proved rather effectively when a true iceberg 50 feet high grounded off the Spit at Ridley Beach in 34 fathoms of water,

while a névé-berg approximately 90 feet high sailed majestically past between it and the land. Soundings subsequently proved that no deeper channel existed which could account for this difference in behaviour. It must, therefore, have been the result of the difference in specific gravity.

Névé-bergs have much the same glistening white colour as the tabular icebergs of class (1*a*), but are slightly more flocculent in appearance. Included in this subdivision must come all bergs formed from ice-sheets due to the rapid accumulation of snow on sea ice. They therefore grade into the heavier floes of Level-Ice which reach, after three or four years' growth, a thickness comparable with the thinnest tabular icebergs such as are derived from the lower portions of Shelf-Ice of the Ross Barrier type.

(2*a*) *Weathered Icebergs.*—Class (2*a*) is a convenient subdivision for the inclusion of all icebergs derived from any type of class (1) by weathering. After the original contours of the icebergs have been destroyed by frequent submersion, and often by overturning, it is quite impossible to tell them apart without boring well into them and examining the internal structure, which may have escaped modification by water. As this is impossible in the case of the great majority of icebergs, some general group is required to include all icebergs in an advanced stage of denudation, whatever their origin may have been. Examples of icebergs of such indeterminate type may be seen in Plates CCLXXXIX and CCXC. Many of the bergs seen in the pack, and many stranded at winter quarters, must be relegated to this group. In the latter situation we have commonly observed the conversion of bergs of one type or other of class (1) into bergs of class (2*a*) by overturning. As this process often takes place comparatively early in the life-history of a berg, the number of bergs under this heading is very many. Their chief characteristic is an infinite variety of form. They have often more or less rounded contours, but may show jagged pinnacles, columns and towers of the most bizarre shapes. They are naturally rather smaller than the bergs from which they are derived through the agency of the weathering processes. A quite common form is a tent-like shape, due to quicker solution at the sides of the former base and then a symmetrical overturning ; on the other hand, overturning usually takes place suddenly, owing to the calving of a large piece of the submerged portion of the berg. It is at this time that the pinnacles and towers of the overturned berg are very often formed.

Within this class and the next must fall a large number of small icebergs which have not been overturned or weathered to any great extent, but which have had their origin in the breaking up of a heavy icefoot, or the swamping of hummocky-floes in autumn with spray ice. The latter accumulations may reach a considerable size, and the masses must be classed as bergs rather than as pressure ice, since they have the appearance of bergs and behave like them in response to the action of the wind and the deeper currents.

(2*b*) *Bergy Bits.*—The final class of recognisable iceberg material is the bergy bit. This may be an original, somewhat weathered, fragment of small size, as those just mentioned above.

It may, on the other hand, perhaps be derived from a glacier stranded at or near sea level, or possibly even from a sheet of Piedmont-Ice resting on a shore platform and therefore separating with difficulty and in small pieces. Bergy bits may also quite commonly arise from the breaking up of larger icebergs.

A typical piece is figured in Plate CCIV, where it is shown stranded off a rocky coast in shallow water and surrounded by a narrow tidal platform and by sea ice. The only difference between classes (2*a*) and (2*b*) is one of size. Upon the sea ice breaking away in the following summer, the majority of the larger pieces of ice would rapidly have their edges worn off and become typical "growlers."

Plate CCXCI shows the result of an iceberg charging a glacier face.

CHAPTER XIII.

GEOLOGICAL CLIMATES OF THE ANTARCTIC.

I.

In recent reviews on palæography, particular attention has been paid to the physical, palæontological and palæobotanical evidence from which deductions as to the probable climates of the geological past can be drawn. Much the most striking of the discoveries of the last few years in this direction has been the establishment, beyond reasonable doubt, of certain geological Ice-ages, during which a great part of the world has been subjected to glacierisation even more severe than that at present in existence on the Antarctic Continent and Greenland.

At least three times in the history of the world clear evidence of major Ice-ages extends over areas continental in extent; on several other occasions the more sporadic occurrence of tillites, glaciated pavements, or erratics, points to the existence of glacial conditions and frigid temperatures over smaller areas for shorter periods.

The more important of these periods of local or general refrigeration are indicated in Table XVII.

TABLE XVII.—Glacial Periods.

Main Proved Glacial Periods.	Local Glaciation.	Countries where Developed.	Remarks.
(1) HURONIAN	—	Canada	Pre-glacial surface an undulating surface of low relief.
(2) PROTEROZOIC	—	India Africa Norway	Possibly two separate glacial periods combined. In Norway probably low land as pre-glacial surface.
(3) PROTEROZOIC or LOWER CAMBRIAN	—	China Australia	Middle latitudes N. and S. of Equator. Australian geologists claim this Ice-age in Australia as Lower Cambrian; United States geologists insist that here also it is Proterozoic.*
(4) DEVONIAN	—	S. Africa	
(5) PERMO-CARBONIFEROUS	—	Australia S. Europe Brazil Africa India	Middle to low latitudes. Seasonal climate in N. and S. Marked inter-glacial periods. Developed on plateaux of low relief and mountains not particularly glaciated.
(6) —	Cretaceous	—	
(7) PLEISTOCENE	—	Worldwide	Particularly effective in high latitudes. Several inter-glacial periods. Chiefly developed on high plateaux. The only glaciation yet proved in Antarctica. Apparently began there in Eocene or Oligocene times, and has been interrupted by inter-glacial periods.

* Information has recently been received from Australia to the effect that Professor David, who has re-examined the exposures, now agrees with the United States geologists in their view of the Proterozoic Age of these deposits.

It is within the scope of the present memoir to consider the relations of the Antarctic regions to these glacial periods or "Ice-ages," and also to the much greater time-intervals during which conditions were more genial. With this in view, it is the writers' intention first to review the available evidence of Antarctic climate; secondly, to contrast and compare such evidence and the conclusions drawn from it with those relating to other regions nearer the Equator; and, finally, to discuss rather tentatively some of the theories propounded to account for the occurrence of climatic changes on a world-wide scale. It may be that little which is original can be added to what has already been for many years a favourite subject for philosophical speculation. On the other hand, nothing but good can result from further examination of the facts, and, in particular, from the discussion of the particular significance of the palæoclimatic evidence from a Polar continental area.

The record of the sedimentary rocks of the Antarctic Continent and its outlying islands, so far as elucidated at the present date, is set forth in Table XVIII, which contains the principal strata arranged (so far as is possible) in chronological order of decreasing age.

TABLE XVIII.

(1) PRE-CAMBRIAN.—*South Victoria Land.*

(*a*) Limestones of the New Harbour region.
(*b*) Graphite and pyrites schists of the Terra Nova Bay region.
(*c*) Slate-Greywacké formation of Robertson Bay.
(*d*) Silicified limestones and cherts and glauconitic sandstone, with casts of radiolaria, occurring erratic between 74° and 78° S. latitude.

(2) CAMBRIAN.—*South Victoria Land and Weddell Sea.*

(*a*) Archæocyathinæ limestones of the Beardmore Glacier and Weddell Sea.

(3) SILURIAN.—*South Orkney Islands.*

(*a*) Slates, greywackés, etc., of South Orkney Islands.

(4) DEVONIAN.—*South Victoria Land.*

(*a*) Shales with fish scales from Granite Harbour.

(5) PERMO-CARBONIFEROUS TO RHÆTIC.—*South Victoria Land and Adélie Land.*

(*a*) Beacon sandstone from Carmen Land to Adélie Land.
(*b*) Bay of Whales conglomerate. (?)

(6) JURASSIC.—*Graham Land.*

(*a*) Greywackés and slates of Hope Bay.

(7) CRETACEOUS.—*Graham Land.*

(*a*) Sandstones of Snow Hill and Seymour Island and of Cockburn Island.
(*b*) Moraine-like mass at Cape Hamilton.
(*c*) Moraine-like mass on mainland near Cape Karl Andreas.

(8) TERTIARY.—*Graham Land and South Victoria Land.*

(*a*) Upper Oligocene and Lower Miocene sandstones with plants and lamellibranchs from Seymour Island.

(*b*) Miocene limestones of Campbell Island.

(*c*) Conglomerate with dolerite pebbles found erratic on the Stranded Moraines, McMurdo Sound.

(*d*) Volcanic glacial agglomerates.

(i) Cape Hamilton.

(ii) Cape Adare.

(iii) Possession Island. (?)

(*e*) Pliocene pecten agglomerate of Cockburn Island.

(9) PLEISTOCENE AND RECENT.—*Antarctica generally.*

(*a*) High-level moraines :—

(i) Beardmore Glacier region.

(ii) McMurdo Sound region.

(iii) Granite Harbour region.

(iv) Terra Nova Bay region.

(v) Robertson Bay region.

(vi) Graham Land region.

(*b*) Raised beaches :—

(i) Graham Land.

(ii) South Victoria Land.

If the individual formations from this table are examined in detail as regards the light which they throw on past Antarctic climatology, it should be possible to gain some idea of climatic conditions over a considerable portion of that period of geological time which has elapsed since the evolution of highly organised forms of life. Some inferences may also be drawn from the rocks of the earlier formations, though necessarily as we search further back in the record the palæoclimatological evidence becomes correspondingly scantier.

(1) PRE-CAMBRIAN.—*South Victoria Land.*

As might be expected, the evidence provided by the Pre-Cambrian sediments is meagre in the extreme. The rocks are in the main too altered to permit conclusions to be drawn from the mineral elements composing them, while such traces of organic material as may have existed have been obliterated during the dynamical and thermal changes which have taken place since the strata were laid down. There are, however, certain indications from which very tentative deductions may be drawn. For instance, the presence of limestone on a large scale is itself indicative possibly of the presence of fairly warm seas. Again, the abundance of carbon in the form of graphite, both in the marbles of New Harbour and in the younger schists of the Terra Nova Bay region, is suggestive of sufficient oceanic warmth to permit the existence of algæ and other similar forms of vegetable life in large quantities.

A third piece of evidence tending towards a similar conclusion is perhaps the occurrence of sandstone containing casts of radiolaria on the South Victoria Land coast. As, however, this rock has only been found erratic, neither its age nor its place of origin is known with any certainty.

In the Robertson Bay slate-greywacké formation, on the other hand, nothing has yet been discovered to which an organic origin may with certainty be attributed. These rocks have certain lithological characteristics strongly suggestive of an origin on the shores of a continent where frost and thaw action played a prominent part.* Here, again, we are left in the dark as to the age of the rocks. They are, however, certainly either Proterozoic or older Palæozoic. They have been somewhat altered by dynamical metamorphism and are strongly cleaved. The majority of the more resistant of the constituent minerals of the coarser members of the series are, however, unaltered. The presence of extremely angular fragments of quartz, in some cases several times as long as they are broad and extremely sharp-edged, can hardly be explained other than by very strong frost action. Such frost action as might take place either in an arid hot or arid cold climate, with considerable daily temperature range on either side of 0°C. Much of the material in these rocks is strongly suggestive of the clastic material to be found in deposits on a landmass exposed to such a climate to-day, while the deductions drawn from this solitary fact are supported by the presence of a fair proportion of fresh unaltered felspar. Thus, in these rocks, we may possibly have the Antarctic representatives of the late Proterozoic or early Cambrian glacial periods, of which abundant evidence has been forthcoming from other regions of the globe. The Antarctic evidence is very meagre, however, for similar results might conceivably be brought about by subaerial weathering in an elevated country exposed to the temperature extremes of a hot desert climate. A conglomeratic grit (described by Dr. Rastall as very similar to the Ingleton grit of Cumberland) which probably belongs to this formation, affords some evidence of formation under continental conditions as a residual wind-sorted soil mantle.† Here again, however, the conglomerate described was "erratic" on an ancient moraine, and little reliance can be placed upon deductions drawn from its constitution as applied to any particular geological age.

As regards the geological age of the whole series, three things of importance may be noted. These are—

(*a*) the occurrence of a band of peculiar nodules somewhat suggestive of altered shelled fossils;

(*b*) the presence of abundant iron pyrites, which suggests an organic content to the sediments from which they are derived;

(*c*) the fact that the larger grained sediments containing recognisable rock fragments have, in large part, been derived from the weathering of a very similar older sedimentary series not metamorphosed to any great extent. Fragments of old volcanic rocks which are quite unaltered, though much weathered, also occur.

* The slate-greywacké formation of Robertson Bay, South Victoria Land. Rastall and Priestley "Scientific Memoirs," 'Scott Antarctic Expedition, 1910–13.'

† Rastall and Priestley, *loc. cit.*

All three pieces of evidence, slight and uncertain as they are individually, indicate that the rocks are not likely to be older than the late Proterozoic, while they may easily be of early Palæozoic age. They are certainly, however, of quite considerably older age than the Devonian shales at the foot of the Beacon Sandstone. For the purposes of the present review, we have therefore classed them as latest Proterozoic, such a decision being confirmed by the fact that the Cambrian limestones of the Beardmore Glacier area, are much younger in appearance.

(2) CAMBRIAN.—*South Victoria Land* and Weddell Sea.*†

(*a*) *Limestones with Archæocyathinæ and calcareous Algæ.*

The earliest known Antarctic fauna is represented by fossil organisms embedded in limestone fragments found, in the one case, erratic on the Beardmore Glacier; in the other, as an iceberg-borne deposit at a depth of 1775 fathoms near the entrance to the Weddell Sea. We have thus no direct evidence of the actual extent of these limestones, though, indirectly, their occurrence in two such widely separated localities is proof positive of a very considerable range. When to this is added the fact that a great proportion of the whole body of the rock fragments secured on all three occasions consisted either of Archæocyathinæ or of Epiphyton, the prolific nature of the Cambrian fauna of the Polar seas appears certain. Huge reefs of coral and algæ living in association—much as the coral reefs of the present day, but possibly even of greater size —must have existed through some degrees of latitude at least. The two localities in which the fragments have been found were on opposite sides of a continent many hundreds of miles in width. They are on opposite sides of the great continental ice-divide also and, unless the beds lie exactly under and about the divide, they must be very widely distributed. Their occurrence in the Weddell Sea is another link in the chain of evidence binding Coats Land and Prince Regent Leopold's Land to a main Antarctic Continent, thus further limiting the possible extent of the hypothetical twin land-mass of which many geologists believe Graham Land to be the northern extremity.

The occurrence of the Archæocyathinæ and Epiphyton on a large scale in Cambrian Antarctic seas is (if any faith may be placed in the principle of the elucidation of past climates by analogy with the conditions under which the present allied faunas of the world flourish) definite proof of a fairly high temperature in the Cambrian Antarctic seas. The position of the remains shows that these seas must have stretched, certainly very nearly to, possibly right across, the present site of the Pole. Corals and their associated calcareous algæ cannot, at present, exist outside of tropical seas. The widespread occurrence of the Archæocyathinæ in Cambrian times has been used by many writers as evidence of the existence of uniformly warm seas of world-wide extension in the Cambrian epoch.

* 'Shackleton Antarctic Expedition, 1907–1909,' "Geology," vol. 1, David and Priestley.

† 'Scottish National Antarctic Expedition, 1902–1904,' "Cambrian organic remains from a dredging in the Weddell Sea," W. T. Gordon, D.Sc.

Yet, it must be admitted, a comparison between Antarctic and Australian forms of Archæocyathinæ brings to light the fact that all Antarctic forms yet discovered are either embryonic or dwarfed. They bear the stamp of having had to struggle for their existence in rather an unsuitable environment.

Further search may bring to light large forms, but in the limestone yet found by the three expeditions no fragments belonging to individuals of large size have been seen. The present evidence is, therefore, in favour of the hypothesis that Antarctic Cambrian seas were somewhat colder than those of what are now the warm temperate and tropical zones. Such a climatic differentiation is what man, with his tendency to consider the human period as the normal rather than the abnormal, would expect. It could, however, have been only slight, for Archæocyathinæ and calcareous algæ, even of dwarfed types, are not likely to have flourished in such profusion as they appear to have done here, in anything colder than temperate seas. This main conclusion should be borne in mind before making too much of the tendency to zonal climatic differentiation which is undoubtedly indicated by the small size of the Antarctic specimens, together with their markedly senile characters, the corallites having strongly thickened walls and septa and an abundance of adventitious structures in the interiors of the cups.

(3) Silurian.—*South Orkney Islands, West Antarctica.*

(*a*) *Slates, greywackés, etc., of South Orkney Islands.*

The next Antarctic sedimentary strata whose age is definable are the shales, greywackés, etc., from the above locality.

The Middle Silurian age of these rocks is deduceable from the fossils found in them, though these fossils are not sufficiently numerous or of the right type to afford any reliable information as to climate. A careful examination of the lithological characters of the sediments might bring to light suggestive facts, but the northerly situation of the islands in any case would minimise the value of any deductions which might otherwise be drawn.

(4) Devonian.—*South Victoria Land.*

(*a*) *Shales of Granite Harbour.*

At Granite Harbour, the Western Party of the Scott Expedition examined erratic blocks from shale beds which lay *in situ* a little further up the Mackay Glacier, where they apparently lay conformably below the sandstone which formed the basal beds of the beacon sandstone. In these shales were found scales of fish which are confidently referred by Smith Woodward to the Devonian period. These rocks apparently mark the beginning of the submergence of the shores of the Antarctic peneplane which was to allow the deposition of thick-bedded strata throughout late Palæozoic and early Mesozoic times, the upper limit of the water-laid sediments being certainly no older than Rhætic.

Neither palæontological nor lithological evidence from the shales is, however, sufficiently definite to afford certain means of determining the climate of the region from which

the material was derived. The absence of any sign of glacial tillites or of erratics carried by floating ice is, perhaps, suggestive of a much milder climate than the present, but even this fact cannot be given too much weight, since few exposures have been visited and little rock seen. The finder of the shales (F. Debenham) is, however, of opinion that they were deposited under estuarine conditions, and, if this is correct, the fact argues a widely different climatic environment from that prevalent to-day.

(5) Permo-Carboniferous to Rhætic.—*South Victoria Land and Adélie Land.*

(a) The Beacon Sandstone formation.

By far the most striking and characteristic feature of the topography of South Victoria Land is the tabular mountains caused by the block-faulting of country capped with the horizontally bedded rocks of the Beacon Sandstone whose fossils have—rather indefinitely—caused its assignment to the above periods.

If the Devonian shales really are, as Debenham believes, conformable beneath the sandstone series, then, in the absence of other breaks, we must recognise in this formation a sequence of deposits right up to Rhætic times, the latter age being indicated by fossil wood and spores—probably from the upper beds—in the Priestley Glacier region. The comparatively small thickness of the sandstone, however, and the fact that the majority of beds examined are such as to point to rather quick deposition, incline the writers to believe that somewhere in the series unconformities, representing the lapse of considerable time intervals, must exist.*

The Beacon Sandstone has now been examined, either cursorily or thoroughly, in four separate regions in South Victoria Land,† and also in Adélie Land. The broad feature as affecting climate, common to all exposures, is the presence of a relatively large quantity of woody or carbonaceous matter, or of fossils after woody matter, throughout a considerable thickness of the sandstones.

Undoubted plant fossils have been found from several horizons.

Beds of coal of somewhat poor quality have been reported from at least two localities. The type plant of the Glossopteris flora has been discovered in great abundance at the Beardmore Glacier, within a few degrees of the Pole. There can be no doubt at all that, throughout a considerable portion of this time, the climate of large regions of this part of Antarctica was such as to favour the development of a relatively prolific flora, though one of a type which is associated in other countries with evidences of the great Permo-Carboniferous glaciation. Indeed, the opinion is held by many eminent

* The fossil wood specimens from the Priestley Glacier, named by A. C. Seward "Antarcticoxylon priestleyi," have been found by J. Walton to show marked affinities to "Rhexoxylon." It is possible that the re-examination of the specimens at present taking place may modify the estimate of the age of the upper limit of the Beacon Sandstone, thus bringing the conclusions more into line with the lithological evidence.

† Amundsen brought back no Beacon Sandstone, but he collected at only one spot, "Mount Betty." There appears to be no reason to believe that the Beacon Sandstone formation dies out before Carmen Land is reached ('The South Pole,' Roald Amundsen).

palæobotanists that Antarctica itself may have been the original home where the development of the Glossopteris flora took place, and whence it spread to South America, Australia and South Africa. There seems, indeed, every reason to countenance this view.

So much for the salient feature of the Antarctic climate of the late Palæozoic and early Mesozoic times. Let us now examine the evidence from each district in turn, in the endeavour to define more closely the Antarctic climate of this era.

If we work from south to north along the block-faulted coast which presumably stretches from Carmen Land to Adélie Land through 20° of latitude, we shall consider the localities in the following order :—

(1) Beardmore Glacier region.
(2) McMurdo Sound and Ferrar Glacier region.
(3) Granite Harbour region.
(4) Terra Nova Bay region.
(5) Adélie Land.

(*a*) *Beardmore Glacier region.**

The occurrence of coal seams in the upper Beacon Sandstone of the Beardmore Glacier is sufficient proof of the existence in these times of a climate very different from that of the present day. Lumps of rotten coal and of impure carbonaceous shales were literally full of Glossopteris remains, so numerous as to remind Professor Seward, who described the plant fossils brought back by the Scott Expedition, of "certain beds in South Africa and Australia packed with the same type of leaf."

He goes on to say later in the same paragraph, "the occurrence of coal-seams and carbonaceous bands favours the view that the windswept hills of the Antarctic continent, though themselves sparsely clad with vegetation, overlooked some sheltered lowlands covered with the gregarious Glossopteris and its associates." Undoubtedly, the climate of this region must have been comparatively mild and somewhat humid, though the existence of seasons is suggested by the banding which is decipherable in the specimen of much decomposed wood brought back by Shackleton's southern party from the same locality. As regards the chronological extension of the mild period, Wild reports at least 25 feet of coal in seven seams, with sandstone and shales intervening.† Obviously, such a thickness must have taken a considerable time to accumulate under the most favourable conditions. If, as the lithological character of many of the rocks suggests, the neighbouring highlands were windswept and arid, and, therefore, devoid of any great amount of vegetation, this minimum time must be very considerably extended.

The lithological evidence from the sandstones and "quartzite" of the Beacon Sandstone of this region points towards the great majority of these having been deposited in a climate where water played a somewhat subordinate role, and "freeze and thaw" action a rather predominant one. Conglomerates appear to be less common than

* 'British Antarctic ("Terra Nova") Expedition, 1910.' "Natural History Report. Geology," vol. 1, No. 1, pp. 1–49. "Antarctic Fossil Plants," A. C. Seward, F.R.S.

† 'Shackleton Geological Report,' vol. 1, David and Priestley.

elsewhere, though this may be more apparent than real, since such specimens would tend to be absent from collections of small fragments made by explorers who were not trained geologists.

The basal limestone breccia, in which the fragments of Archæocyathinæ occur, is typically a non-aqueous deposit. The presence of a large proportion of unaltered original felspar in the rocks described by Mawson on the first Shackleton Expedition suggests the rapid deposition of detritus which was not appreciably acted upon by percolating water.* The angular nature of the grains in the same rocks suggests an absence of trituration in running water, or along a shallow coast. Amongst the specimens collected by the Scott Southern Party, some are much more suggestive of water action, pointing to periods of milder climate and slower deposition, but the general facies of the deposits suggests relatively quick deposition of mechanically-derived sediments along a steadily subsiding coastline.

The 300 feet of interbedded sandstones, shales and coal seams, on the other hand, appear to belong to a period of comparative equilibrium with frequent minor oscillations, during the upper phases of which vegetation rapidly collected and grew *in situ* under estuarine conditions.

(b) *McMurdo Sound and Ferrar Glacier region.*

From the second of the regions visited by the three British Expeditions, and particularly the Ferrar Glacier, where Hartley Ferrar first studied this formation, the evidence is of somewhat similar nature.† On the whole, however, there is a relative paucity of carbonaceous remains which cannot be accounted for by the indurating and destroying influence of the dolerite intrusions which are perhaps more dominant here. There appears certainly to have been less vegetation in this area, while the wind-rolled sand grains composing many of the sandstones are highly suggestive of a climate considerably more arid than in the Beardmore district. Ferrar describes conglomerates which undoubtedly owe their rounded pebbles to water action, and, again, some of the sandstones are suggestive of the work of running water or of wave action. On the other hand, a breccia with almost cubical fragments of quartz with extremely sharp angles bespeaks frost action without subsequent re-sorting, and once again, fresh undecomposed original felspar is a prominent constituent of some of the beds.‡ On the whole, the evidence, though somewhat conflicting, is suggestive of alternations of marine and continental deposition on a somewhat arid coast, with occasional heavy rains and certainly with considerable frost action.

(c) *Granite Harbour region.*

At Granite Harbour, which was thoroughly examined by a party of the Scott Expedition containing two geologists (Debenham and Taylor), practically the same phase of the Beacon Sandstone was encountered as that just described. Here, coal

* 'Shackleton Antarctic Expedition, 1907–9,' "Geology," vol. 2.

† 'National Antarctic Expedition, 1901–4,' "Natural History," vol. 1, "Geology," H. T. Ferrar.

‡ 'National Antarctic Expedition, 1901–4.' "Natural History," vol. 1. "Geology." Report on the Rock Specimens," etc., G. T. Prior.

measures comparable with those of the Beardmore Glacier exist, and, though the seams were inaccessible, blocks of good coal were collected from the moraines. Lithologically, Debenham states, the sandstone strata bear the stamp of deposition under estuarine conditions, on the flank of a continent with predominantly arid climate and with large temperature range, but with local areas where conditions were suitable to profuse vegetable life. Here, as in the Ferrar Glacier region, the strata were observed to be laid down upon the border of a peneplain of low relief and senile contour. This fact may, perhaps, be of importance in attempting to explain the apparent difference of intensity of the glacierisation of Permo-Carboniferous times in low latitudes and in the Antarctic.

(*d*) *Terra Nova Bay region.*

From the Terra Nova Bay area, one or two interesting pieces of evidence can be adduced. To begin with, the discovery of fossil stems 12 to 18 inches in diameter, and of fragmentary impressions of even larger trees, is suggestive certainly of climatic conditions in the neighbourhood of what is now the Priestley Glacier, in which forests of trees of considerable size could flourish. Almost every specimen of sandstone contained more or less carbonaceous material. Indeed, the outstanding feature of the Beacon Sandstone of this region was the relative abundance of such remains, a profusion which, as regards woody material, seems to be equalled only in the Beardmore Glacier area. The fragments of the stem described by Professor Seward under the name Antarcticoxylon priestleyi* shows, however, extremely well-marked growth rings, suggestive of a climate with considerable seasonal variation. Such wood might be compared with that at present growing in Arctic continental regions in high latitudes. The climate here, possibly, nearly approached the limit of variation which large trees can support.

The lithological evidence is again in favour of the prevalence of climates favourable to a considerable amount of frost action. In addition, a volcanic phase, while possibly producing a local amelioration of climate, must have added considerably to the difficulties of the plant inhabitants. Indeed, the presence of large quantities of highly carbonaceous tuffs and of bituminous sandstones is strongly suggestive of a frequent wholesale destruction of vegetation, which could only be made good by fresh migrations from neighbouring more favoured areas. The waterworn pebbles of the conglomerates again, however, attest the presence of streams of considerable velocity and probably of considerable size. Conglomerates are more common here than in any district where the Beacon Sandstone has been examined, and it is in these conglomerates that many of the best preserved of the fossil wood specimens are to be found. Once again, arkoses with unweathered original felspars are common, and add their quota to the weight of evidence in favour of a rather desiccated climate. The impression is gained of a desolate arid landscape, with occasional heavy seasonal rains washing large quantities of rolled detritus into the sea and with neighbouring lowland tracts, or even sheltered upland

* Since the above was written, the material has been further examined by J. Walton, who will shortly be publishing a note on the fossils. He identifies the wood as belonging to the genus "Rhexoxylon." Its nearest analogues are found in the Molteno Beds of the Stormberg Series of the Karroo Formation of South Africa.

valleys, where local more uniform precipitation, or fertile oases with permanent water supply, permitted the growth of a quite abundant local vegetation of a hardy type. The comparative activity of water erosion may conceivably be correlated with the frequent eruptions of volcanic dust and ashes which marked the prevalence in this region of extrusive igneous action.

There remains one fact which requires mention—the occurrence on a moraine on Mount Larsen of a fragment which Mawson describes as a "true tillite of older age." Was this derived from the Beacon Sandstone formation? If so, it is the solitary instance we have so far discovered of a glacial phase in the whole of this great sedimentary formation. It requires mention, though it is, of course, problematical whether it belongs to this period, and whether, even if it does, it is of any considerable extent. One of the most striking features of the Permo-Carboniferous (?) deposits of the Antarctic continent is the fact that in this present home of the Continental-Ice sheet, there have been found no evidences of a marked glacial phase at a time when Australia, South Africa, South America and India—regions within a few degrees of the Equator—were strongly glaciated.

It is unbelievable that such deposits of any extent could have been missed by sledge parties conscientiously examining every cliff section and moraine across their path. In some cases, trained geologists accompanied the parties. It is true that exposures—although ideal when reached—were few and far between, but, on the other hand, the moraines, frequently followed as a convenient avenue of geological and geographical exploration, provided a selection of rocks from all the exposures past the foot of which the glaciers had moved: We are confident that, if the several glaciers traversed had cut through glacial beds (and they have severed the Beacon Sandstone formation from top to bottom) fragments of the tillites must have been encountered somewhere or other. The only glacial beds that could well have been overlooked are local deposits due to valley glaciers. There are many points about the sediments which make it quite possible that such valley glaciers with their local névéfields may have existed.

We have, however, no proof even of this and, on the whole, the evidence is rather for desert conditions with a large temperature range with one extreme below freezing point, but with little moisture to form accumulations of snow and with too high a mean temperature to enable any such accumulations to become perennial.

(*e*) *Adélie Land Region.*

The Australasian Expedition of 1910–1913 have examined typical Beacon Sandstone outcrops in the vicinity of King George V Land.* Once again, the formation contains many carbonaceous layers and some, rather impure, coal seams. The presence of thick deposits of red sandstone is suggestive of long periods of desert climate and, indeed, the evidence of the whole series, points to climates very uniform with those of South Victoria Land at the same time. It has, however, proved impossible to obtain copies of the detailed reports of the Expedition from which more definite conclusions might be drawn.

* D. Mawson, 'Geol. Jour.,' 1914.

(*f*) *Bay of Whales Dredging.*

Mention might finally be made of a number of specimens of conglomerate dredged up from the Bay of Whales which, judging from the included fragments, and from the general appearance of the rock, may quite probably belong to the Beacon Sandstone formation. The rock consists of numerous waterworn fragments of quartzites, schists, and granite set in a fairly coarse groundmass of angular or sub-angular grains of quartz, themselves embedded in carbonate. In its general appearance, it is quite like some of the coarser grits of the Beacon Sandstone which are also locally very full of carbonate. The interest of the rock lies chiefly in its position, which suggests the possibility of a considerable eastward extension of the Beacon Sandstone, perhaps in the range Amundsen saw diverging in a north-easterly direction from south of Carmen Land. When originally examined in the field, the rock was taken for a tillite, but subsequent microscopical and chemical examination has proved the fine grey material of the matrix to be, not glacial mud, but carbonate.

(6) JURASSIC.—*Graham Land.**

While particular attention has been paid to the Permo-Carboniferous to Rhætic deposits of East Antarctica, which are typically developed in the region personally examined by ourselves, perhaps the most striking evidence of mild Antarctic climates is to be found in West Antarctica. On the islands lying off the mountainous coast of Graham Land, the Swedish Antarctic Expedition, under the leadership of Otto Nordenskjöld,† were fortunate enough to make their winter quarters actually on sedimentary rocks containing well-preserved land floras. Of these, the oldest proved to be of Jurassic age and the series was typically developed at Hope Bay, where Gunnar Andersson, the geologist of the Expedition, was detained for the greater part of a winter. The researches of this party were rewarded by the discovery of the remains of a prolific flora of numerous species, embedded in the slates which formed a conspicuous feature of the deposits. This flora has been fully described by Professor Nathorst‡ and T. S. Halle, and for the present purpose, no recapitulation is necessary. It suffices to quote the following sentence from the paper in which the discoverer of the rocks reported his find :—

> "Considered as a whole, this Jurassic flora resembles on the one hand the European Jurassic flora, on the other the upper Gondwana of India (Jabalpur, Kach). From a climatological point of view, there can be traced no difference between the floras mentioned, and in this respect the collection from the Antarctic region might have been gathered on the coast of Yorkshire, as the absence of big-sized Otazamites may be considered accidental. In the abundance of species, the flora from Hope Bay far surpasses all Jurassic floras hitherto known from South America."

* 'The Geology of Graham Land,' J. Gunnar Andersson.

† 'Die Schwedische Süd Polar Expedition und ihre geographische Tätigkeit,' Otto Nordenskjöld.

‡ The flora was described in detail by Halle after a preliminary note by Nathorst ("The Mesozoic Flora of Graham Land," T. S. Halle).

No better evidence could be required of the mildness of the Graham Land climate in Mesozoic times. There is no need to reinforce the testimony of the plants by any close lithological examination of the rocks in which they occur.

The presence of large fronds of delicate ferns in an undamaged condition is proof enough that, here, we are dealing with a flora which, in great part at any rate, existed on the spot. The accompanying bivalves of fresh-water affinities, and the presence of water ferns (*Sagenopteris*) are quoted by Andersson as proof of deposit in a local fresh-water basin.* Considered in connection with the uniformity of the Jurassic flora over the whole of the very wide region where it has been found, this flora of the Antarctic regions must be a clinching argument in the hands of those palæobotanists who claim the absence of any measure of zonal climate similar to that existing in the present age.

It may possibly be owing to the fact of East Antarctica having already been raised or being in process of being raised, that no equivalent rocks have been found in South Victoria Land. On the other hand, it should be pointed out that the top of the Beacon Sandstone has nowhere been examined. The gentle dip of the beds inwards at the inland side of the horst suggests that there may well be succeeding Jurassic beds under the ice which, if exposed, might tell a similar tale.

In the absence of such evidence, however, we have to be content with this somewhat one-sided indication of what the Jurassic Antarctic climate was like. It is extremely unlikely that such a sudden change could take place in the few remaining degrees of latitude as to bring about glacial conditions in the region immediately round the Pole. The evidence appears sufficient to warrant the assumption that, in Jurassic times, the Antarctic regions—like those about the North Pole—enjoyed a climate comparable to that we should by present standards call warm-temperate to sub-tropical.

(7) Cretaceous.—*Graham Land.*†

(*a*) *Marine sediments of Snow Hill, Seymour Island and Cockburn Island.*

For evidence of Antarctic climate in the succeeding geological period—the Cretaceous—it is again necessary to turn to West Antarctica and Graham Land. At Snow Hill and Seymour Islands, and at Cockburn Island, Nordenskjöld examined and described a thick series of soft sandy beds of apparently typical marine shallow-water type, with occasional clays and nodular limestones. In these rocks was found a varied marine fauna including "ammonites, abounding both in specimens and species, bivalves and gasteropods, fish remains and corals — echinids and decapoda (rare)—some scarce pieces of wood." Of all the few plant fossils, only one was determinable, a small twig of a conifer, *Sequoia fastigata*. The general facies of the fauna seems to be still, in the main, warm-temperate, but at least one bed of pygmæan forms suggests the possibility of a refrigeration, possibly the forerunner of the greater falls in temperature to come. Further researches may bring to light more plant fossils which may enable more precise deductions to be drawn. It is interesting to note that the one determinable

* As the affinities of *Sagenopteris* are not yet well known, this deduction is not perhaps quite sound.

† Otto Nordenskjöld, *loc. cit.*

plant fossil finds its nearest analogue in the "Cenomanian of Europe and the Cenomanian and Senonian of Greenland."

Once again, we are entirely without climatic record, or, indeed, so far as is known at present, without any stratigraphical record of this period in East Antarctica. It is probably to this period that we must assign the vigorous intrusive igneous action which was world-wide in its scope, being equally felt in South Africa, Australasia and Antarctica, to name three localities, only. Such immense continental movements of igneous magma must have resulted in or been the result of a disturbance of isostatic equilibrium. This may have found one expression and compensation later in Tertiary times in the block-faulting movements which gave East Antarctica its present form. Even did evidence of Cretaceous climate in East Antarctica formerly exist, it has long been swept away, hidden beneath a mantle of ice west of the great rock divide, or beneath the waters of the Ross Sea. In this connection, it is interesting to note that, while fragmental volcanic rocks and parasitic cones at Ross Island and Cape Adare contain recognisable pieces of Beacon Sandstone and dolerite, and, in the latter place, also of the slate and greywacké of the Robertson Bay formation, none have been observed which could probably belong to later sediments. The only post-Rhætic sediment known from East Antarctica is a conglomerate containing numerous fragments of dolerite, several pieces of which were found by one of the writers on the Stranded Moraines in McMurdo Sound, in 1908. These are referred to in the petrological Memoir of the Shackleton Expedition* and are believed to be of late Tertiary age.

(*b*) *Moraine-like mass at Cape Hamilton* (*Graham Land*).

Immediately above the Cretaceous beds at Cape Hamilton lies a deposit of great climatic importance, which is described by its finder as follows :—

> "A moraine-like mass, some metres in thickness. In a clayey matrix lie numerous angular fragments of crystalline rocks foreign to the locality (granite, etc. No volcanic rocks or porphyries were noticed among these fragments of plutonic eruptives and crystalline schists). Also pieces of 'claystone' were noticed. The largest of these lumps of foreign rocks did not exceed half a meter in diameter ; most of them were much smaller."

Above this, again, lies a bed of "clayish sandstone," two metres in thickness, with numerous small fragments of basalt, and exhibiting evidence of current-bedding. Mention has already been made of the sandstone at Cockburn Island, which was found to be crowded with pygmæan forms of life such as might be expected to result from the encroachment of colder conditions upon a marine fauna long developed in, and habituated to, more genial conditions.

It appears probable, again, that in this moraine-like bed above the Cretaceous—it may be still in Cretaceous times, it may be in early Tertiary, but certainly before the outpouring of the Oligocene basalts—we have visible evidence of one swing of the climatic pendulum as the Tertiary refrigeration set in. Angular rock fragments in

* 'Shackleton Expedition, 1907–9,' "Geology," vol. 2.

a clayey matrix are strongly suggestive of glacial action on a comparatively large scale.

Of the same age, perhaps, is a deposit on the mainland coast between Cape Karl Andreas and Cape Gunnar, which Andersson describes as follows :—*

> " Here, a shore nunatak exhibits a coarse conglomerate with boulders up to 2 metres in diameter. In general, the mass is quite unstratified and really much like a bottom moraine, though the rock is old and seems to have taken part in the mountain folding."

The time of the folding is believed to have been between Cretaceous and Upper Oligocene, and it is therefore quite likely that the two deposits may have been more or less contemporaneous. If this is so, it should be noted that these form the first definite evidences of glacial conditions, on anything like a large scale, in the geological history of the Antarctic, as partially unfolded before our eyes. Both in Proterozoic (?) and in Permo-Carboniferous times, suggestions of local arid spells which may possibly have been cold have been cited. Nevertheless, the normal conditions so far have undoubtedly been mild, compatible with the flourishing of vegetation on a large scale, or the development of warm-water faunas, equally unsuited to the present Antarctic conditions.

(8) TERTIARY.—*Graham Land and South Victoria Land.*

(a) *Upper Oligocene to Lower Miocene Sandstones of Seymour Island.*

To Graham Land, the botanical museum of West Antarctica, we must again turn for the evidences of a Tertiary flora which is proof positive that, if glaciers commenced to flourish in early Tertiary times, the beginning of the ice age was accompanied by similar climatic fluctuations to those which marked its close in more northern latitudes. Not yet can the extension of the Continental ice-floods have swept the Antarctic flora into the sea, or, if such a thing happened, "land connections" with South America must have permitted comparatively rapid repopulation by migration, immediately conditions once more became sufficiently ameliorated.

In the words of Prof. Nathorst in his preliminary report on this Tertiary flora :—

> " Les Fougères y sont assez communes et appartiennent à plusieurs espèces différentes, mais les débris sont de petites dimensions et difficiles à déterminer. Une conifère a feuilles distiques rappelle assez, à première vue, l'aspect d'un Sequoia, mais un examen attentif semble indiquer qu'il s'agit d'un autre genre. Une seule feuille isolée semble appartenir à une Araucaria,† assez voisin de l'Ar. brasiliensis. Les feuilles de Dicotyledones sont généralement petites et présentent le même facies que celles de certaines flores tertiaires de l'Europe méridionale. Comme fait intéressant il y a lieu de signaler quelques feuilles de Fagus."

* J. Gunnar Andersson, *loc. cit.*

† Araucarian wood in trunks up to 2 feet in diameter has been described from Kerguelen Island. These plant remains are preserved between sheets of Tertiary lavas which are quite probably of similar age to the great volcanic outpourings of East and West Antarctica. (H. R. Goeppert, 'Bot. Centralblatt,' bd. v, p. 378 ; A. C. Seward, *loc. cit.*)

The presence of dicotyledons and in particular of beech leaves, gives the flora a familiar and homely appearance. Its likeness to the homotaxial flora of Southern Europe is proof enough of at least a temperate climate. The value of the fossils as evidence of strictly Antarctic climate is lessened by the fact that they occur in a marine deposit. Nevertheless, the preservation of such delicate fossils as leaves of beech, &c., strongly suggests that, though " erratic " in the strict sense of the word, they grew on a land not far from the place where they were found.

The probabilities are really all in favour of their derivation from some portion of what we now know as Graham Land, or even from further south. From the affinities of the molluscan fauna, which was contemporaneous with this flora, little that is definite can be learnt as regards climate. It bears strong resemblance, however, to that of the " Patagonian molasse," the majority of species being common to both, and this is perhaps suggestive of waters of much the same temperature in the two localities. The presence of bones of several species of penguin suggests, at any rate, a cool coastal climate ; that of the remains of a zeuglodon is of no value, since this animal approached in type to the killer whale and probably enjoyed an equally widespread distribution. Considering all the evidence together, we are perhaps justified in visualising conditions similar to those at present existing near the outer limits of the temperate zones of to-day, though the presence of some 50 sub-tropical forms and only 20 temperate forms in the flora suggests a somewhat warmer environment.

It is quite likely that, further to the south, local glacierisation persisted from the early Eocene beginning of the glacial period of which some evidence has already been cited from West Antarctica.

If this interpretation is correct, then the Oligocene-Miocene flora and fauna either persisted in spite of the approach of glacial conditions, or developed in, or migrated into, the area during an interglacial period, much as happened once and again during the Pleistocene Ice-Age in the northern hemisphere.

(*b*) *Miocene Limestone of Campbell Island.*

It is to the sub-antarctic islands of East Antarctica that we must turn for the next evidence of Antarctic Tertiary history. Many weighty reasons have been adduced by the scientists who surveyed the Auckland, Macquarie and Campbell Islands south of New Zealand to support the theory that these are remnants of a Tertiary land-mass of continental extent which may have been an important item in a chain forming a " land-bridge " between Antarctica and New Zealand and, through the latter, possibly Australia. Upon Campbell Island, limestones of Miocene age have been found, and the presence of these is a somewhat unreliable piece of evidence in favour of the existence of a milder climate in Miocene times than at present. To this may be added, however, more definite physiographical evidence of the preponderance of water erosion in Tertiary times, when the present drainage lines clearly originated as a stream system in late Tertiary times, to be subsequently modified by the glaciers of the Pleistocene (?) Ice-Age. At the close of the Miocene period, volcanic action broke out, and the results of this have to a great extent obscured the stratigraphical record.

(c) *Volcanic Glacial Agglomerates.*

All over the Antarctic, at all the weak spots and lines produced by the Tertiary earth movements, volcanic action has resulted in the deposition either of immense lava flows, or of aggregates of intercalated lavas and more fragmentary ejectamenta. Over a great portion of the continent, no precise age can be assigned to the deposits, but, assuming the disturbances to have been fairly contemporaneous, the stratigraphical evidence is sufficient to limit the volcanic action to the period between Upper Oligocene and the present day, when it still lingers at such isolated spots as Mount Erebus in Ross Island.

While it is probable that these volcanic deposits, which form a considerable portion of the exposed rock near the headquarters of almost all the Antarctic expeditions, have much defaced and hidden the later portions of the stratigraphical record, in one or two places they themselves bear quite definite evidence of the climatic conditions during portions of the time characterised by their outpouring. At three separate localities have such isolated scraps of evidence been found, all tending to support the assumption that glacierisation was the rule during at least a great portion of the late Tertiary era :—

(i) Amongst the lower volcanics of Seymour Island in West Antarctica, Nordenskjöld* reports the occurrence of a tufaceous breccia with numerous foreign blocks of schist, slate and gneiss. He himself ascribes the formation to the working of ice, since none of the rocks occur *in situ* within 30 to 35 miles. He states that the deposit was probably laid down in water, in which case the erratic blocks must have been carried either by icebergs or by the floating termination of ice-sheets comparable to those at present fringing the continent.

(ii) At Cape Adare, the Northern Party of the Scott Expedition discovered low down in the volcanic series a similar tufaceous agglomerate crowded with what were—from their shape and the diversity of their kinds—undoubtedly erratic blocks. Beautifully facetted blocks of granite and dolerite lay cheek by jowl with more angular and irregularly shaped schists, slates, porphyries, and volcanic rocks, much older in appearance and differing in type from the Cape Adare Tertiary series. The age of the deposit is problematical, but must be comparatively early in the Tertiary volcanic history of South Victoria Land, for the basalts of Cape Adare look distinctly older than those of Ross Island. This particular deposit has been buried beneath many hundred feet of later lavas and tuffs, while, since the cessation of volcanic activity, the eastern deposits of the cape have been cut away by the sea until the peninsula fronts the ocean as a cliff two or three thousand feet high. In the opinion of the finder of the deposit, the Miocene period is the latest to which it can be assigned. The position of the rocks, unless considerable

* Otto Nordenskjöld, *loc. cit.*

changes of level have taken place, suggests an ice flood somewhat greater than the present. This is borne out by the constitution of the enclosed moraine material, the majority of which must have come from mountains at least half a hundred miles to the south and west.

(iii) At Possession Island off South Victoria Land, during the cursory visit of the Ross Expedition in 1841, a specimen of muscovite granite, with fragments of tuff adhering to it, was collected by the surgeon of the Erebus. Possession Island itself is entirely volcanic, and it is likely that further research might bring to light a deposit similar to those described above, in which case further evidence still would be available of the antiquity of the Antarctic Ice-age. On the other hand, the granite specimen may have been torn from the wall of the fissure or pipe through which the volcanic material was forced to the surface. This is a point for further investigation.

(e) *Pliocene Conglomerate of Cockburn Island.*

At Cockburn Island, which stands in the eastern entrance of Admiralty Sound in West Antarctica, an interesting Pliocene marine deposit has been collected. In a conglomerate consisting chiefly of large and small basalt blocks, occur a few erratics of gneiss, granite, &c., which must have been carried to their place of deposition by floating ice. The fauna of the bed is characterised by the preponderance of a very beautiful Pecten, closely allied to one occurring in similar beds in Patagonia (*P. Actinoides*) of which the deposit is believed to be the analogue. It is an interesting commentary on this occurrence that another large and beautiful Pecten (*P. Colbecki*) forms the characteristic inhabitant of the surface of similar deposits in the shore zone along the South Victoria Land coast of the present day. Further evidence of the Pliocene Antarctic climate is afforded by the fact that the cold-avoiding Ostrea, common in the Patagonian deposits, is conspicuously lacking in the Cockburn Island conglomerate. Of the other fossils, 6 out of 12 Bryozoa are now living in Antarctic waters. Mature consideration of the fauna by the discoverers of the deposit have led them to form the opinion that it was laid down in a slightly warmer sea than that in the same latitude at the present time. If this is correct, the deposit thus suggests a milder period within the Tertiary Ice-age. This agrees quite well with the evidence of the early volcanic agglomerates and of the Pleistocene and recent high level moraines, which we will next consider. The present position of the conglomerate several hundred feet above sea-level is eloquent of recent tectonic movements in the Graham Land region.

One factor to which some weight must be given when drawing analogies between the known climates of the Graham Land region as indicated by the fossil floras and faunas, and the inferred climate of the Antarctic regions generally, is the possibility of a land connection stretching right down from South America. One result of such a land-bridge would probably be the persistence of a warm surface current right down into the Antarctic regions, and this would possibly suffice to give a different facies to the marine fauna of the shore zone in particular. Thus, quite possibly, the Pliocene

deposit just considered may be of quite local significance, and have been laid down in spite of the continuance of the Ice-age without much amelioration throughout Pliocene times. The writers, however, consider such a deposit incompatible with any greater extension of the shore-ice fringe than at present exists, so that this period would still appear to be marked by rather less glacierisation than that both immediately before and after it.

(9) Pleistocene and Recent.—*Antarctica generally.*

(a) *High-Level Moraines.*

The evidence for a Pleistocene or recent extension of the Antarctic ice-covering, far beyond its present limits, is overwhelmingly strong from all Antarctic regions where rock is at present left uncovered. Similar evidence is afforded by an examination of any of the sub-Antarctic islands. The weight of testimony is all in favour of the conclusion that this most recent maximum of the ice was the culmination of the Tertiary Ice-age, which, as we have shown above, appears to be the only Antarctic glacial period whose existence is indubitably indicated by the sediments at present brought to light. A general review of the observations made by many Expeditions points to a former thickening of the Continental-Ice by at least several hundreds of feet; to the submergence of valleys now occupied by glaciers by, in some cases, as much as two to three thousand feet; to the swamping beneath the ice-flood of thousands of nunataks and nunakols at present exposed; and to the occupation by ice of portions of the continent at present almost entirely ice-free.

The evidence has been reviewed and summarised in several recent comprehensive publications on Glaciology and does not therefore need recapitulation here. The records of all expeditions which have explored the Antarctic continent and islands are full of such indications. The protagonists of most of the more interesting discussions and controversies on Polar Glaciology have quoted them again and again in favour of one or other of the theories put forward to explain glacial periods and the undoubted fluctuations of climate which together make up an Ice-age. We will therefore content ourselves here with a brief review of the evidence personally encountered by members of the present Expedition in the regions visited by them.

(i) *Beardmore Glacier* (83° to 85° S. latitude).

In the Beardmore Glacier area, the Shackleton Expedition brought back evidence of erratics up to at least 200 feet above the glacier in many places, while at Mount Hope erratics and moraines were found capping the granite top of the mountain at a level of no less than 2000 feet above the adjacent glacier ice. Mount Darwin and Buckley Island, at the top of the Beardmore Glacier, have also been overrun by the Continental Ice-sheet. These observations are confirmed by the sledge parties of the present Expedition.

(ii) *The McMurdo Sound region.*

This area, the headquarters in turn of three great Expeditions, has provided a wealth of evidence, the conclusions from which may be summarised as follows:—(*a*) The valley glaciers providing the outlets from the Continental-Ice across this portion of the horst did, at some comparatively recent time, in portions of their course, reach a height, normally of several hundreds, in places, of 1000 to 1500 feet above the level of the present surface. (*b*) Portions of the coast of the Ross Sea, at present free from ice and reaching to a height of 1000 feet above sea level, have been invaded by land ice having its source on or beyond the main Victoria Land horst. (*c*) Many headlands or nunataks at present standing several hundred feet above the present ice surface have been covered by land ice of sufficient thickness to cause a definite smoothing of their surface. The high-level moraines of this district have been described in detail by F. Debenham in a memoir upon the "Recent Deposits of South Victoria Land."* He arrives at the conclusion that all the phenomena can be explained by a comparatively small increase (600 feet or less) in the thickness of the local ice-sheets, particularly the ice-sheet which was the ancestor of the present Koettlitz Glacier. He attributes the great height above the ice to which the erratics have been forced to banking up against obstacles lying in its course, pointing out the fact that, to the south of Minna Bluff, for example, the Ross Barrier at present reaches a height several hundred feet above its normal height where unobstructed.

While agreeing with his contention that the Ross Barrier which is afloat did not formerly reach much greater thickness than at present in its main mass, and that, as in the case cited, and as still better shown by the flooding of the island behind Framheim, ice will readily climb uphill for considerable distances, the present writers are inclined to be rather less conservative about the degree of glacierisation of the Antarctic Continent at this Ice-age maximum. The reasons for this will be discussed after the other localities visited have been referred to.

(iii) *Granite Harbour.*

Here, the Western Party found no great evidence of a former higher extension of the Mackay Glacier. Mount Suess (Gondola Mountain), which at present stands over 200 feet above the glacier level, has undoubtedly been completely covered, but high-level moraines were not present to any great extent. The inference is that this wide outlet valley—which is at present only partially occupied by its entrenched ice stream—has always been adequate to deal with the outflow from the plateau. It is only where outlets are restricted in number and are comparatively narrow† that one would expect to find the maximum banking up of the ice in the form of unusually thick outlet glaciers.

* 'British Antarctic ("Terra Nova") Expedition, 1910,' "Natural History. Geology," vol. 1, No. 3, pp. 63–100. "Recent and Local Deposits of McMurdo Sound Region," F. Debenham.

† And where the coastal range of mountains is highest.

(iv) *Terra Nova Bay.*

The Northern Party, while in the Terra Nova Bay area, came across similar evidence of former great glacierisation. This evidence has been summarised in the field notes of the geologist of the party as follows:—

> "It is noticeable that the heights at which erratics were encountered were nowhere so great as in the Ferrar Glacier Valley, on Ross Island, or in the Beardmore Glacier area. At the Northern Foothills they were found at a height of 400 feet above the present glacier level, and though in other places no measurements were taken, I consider it unlikely that this height was greatly exceeded. This can be readily accounted for by the fact that great outlets from the plateau occur immediately to the north and south at a much lower level. While, undoubtedly, the volume of ice pouring down the Campbell and Priestley Glaciers was much increased, it is certain that the main outflow would have been, to a greater extent even than at present, by way of the Reeves Glacier and its southern neighbours and at Wood Bay.
>
> "The direction of the grooves on the summit of Vegetation Island (N. and S.) and the grooves and striæ on the bluff to the east of the entrance of the Priestley Glacier (S.E. and N.W.) suggest that there was no great modification of the present drainage lines in this immediate district. What evidence there is tends to the view that the greater flow from the Reeves, and perhaps from the Priestley, Glacier tended to suppress the Campbell Glacier and divert the main drainage of the Melbourne Ice further northwards."

A glance at the map of this area, at the end of the volume, will show that this also is a region where an immense extra outflow could be accommodated without any great banking up of the outlet glaciers. The strong glaciation of Vegetation Island is, however, sufficient proof that the Campbell-Priestley Confluent-Ice was at least several hundred feet thicker than at present and moved seaward with much greater velocity.

(v) *Robertson Bay.*

Perhaps in no place visited by the Expedition was more striking evidence of greater extension of the land ice to be seen than at Robertson Bay. Signs of the ice maximum are clearly preserved in the high-level moraines, 1000 feet or more above sea level, at the end of the promontory of Cape Adare, while the shape of the end of the cape between 800 feet and 1,600 feet is strongly suggestive of the rounding and abrading action of glacier ice moving at considerable speed. Here, also, may be seen clear evidence of stages in the recession of the ice to its present limits. The terrace some 50 to 100 feet above sea level along the back of Ridley Beach may possibly have been the lateral moraine of a prehistoric Robertson Bay glacier. A similar, but more obviously glacial, accumulation extending some 750 yards beyond the present end of the George Newnes Glacier clearly marks another pause in the retreat of the ice.

The significance of the high-level moraines on Cape Adare is emphasised when it is remembered that they are at present separated by 18 or 20 miles of sea-filled fjord from the only glaciers that could possibly be relics of the great ice streams which gave rise to them. Also they stand over 1000 feet above sea level, while the present glaciers front the sea as relatively insignificant cliffs 50 to 100 feet high.

It is, indeed, these great empty bays, straits and fjords which are at present occupied only by arms of the sea, but which were formerly undoubtedly filled to depths of probably one, possibly two or three, thousand feet with ice, which most incline one to take a less conservative view of the degree of glacierisation of the Antarctic Continent at this ice maximum. Gerlache Channel, McMurdo Sound, Robertson Bay, to name only three of them, are all very pertinent examples. Adequate nourishment for the glaciers which formerly occupied and surged along these mighty channels demands a much thicker sheet of Continental-Ice on the mainland of the Antarctic Continent; and if this existed, it is impossible to imagine that its outward flow was not vastly increased in other directions also.

Were the evidence confined to South Victoria Land only, one might postulate the recent diminution as due, not to a decisive decrease in precipitation and accumulation, but to the latest movements of the tectonic adjustment which has, in Tertiary times, formed the horst, and which may, we believe, have exercised a distinct influence upon local desiccation not otherwise easily accounted for.

If, as seems probable, some of the blocks of the Victoria Land horst are still, or have been quite recently, in motion, such a local rise of the coastal ice-divide may, without the intervention of any other factor, account for the local deglacierisation of such regions as the Lister and Sabine areas. Here deglacierisation is most pronounced, and here, perhaps by coincidence, more likely as cause and effect, the highest blocks of the Victoria Land horst occur.

It is, at any rate, a possible hypothesis that recent tectonic movements may have caused the formation of the marked Dry Valleys of the Ferrar and its neighbours and of the John Murray Glacier, by cutting off a great measure of the supply from inland.

It is a striking fact that, in the Robertson Bay and McMurdo Sound areas (and possibly the Beardmore Glacier area), where the mountains are particularly high, there is clear evidence of a dwindling of the glaciers which flowed into the sea by the shortest path, associated with the occurrence of much mightier glaciers running more or less parallel to the general trend of the coastline. We believe all these phenomena to be associated with one another. Thus, to take the case of the Ferrar-Koettlitz region, the great height of the Lister range may be due to an exceptionally great uplift resulting in a cutting off of the supply of the Ferrar and Taylor glaciers. This has caused in its turn a poverty of alimentation in the area. The overflow from the Continental-Ice Sheet has thus been concentrated in the regions to north and south. One result has been the enlargement of the Koettlitz Glacier, which rapidly deepened its valley and reached an immense thickness.

When, however, the evidence is widespread from regions so tectonically diverse

as Graham Land and Victoria Land, some more general cause of the marked deglacierisation which is the most pronounced feature of the recent geological history of the Antarctic Continent must be looked for. There must have been a considerable shrinkage of the ice-covering which has caused the absolute disappearance of glaciers from many of the inlets of the coastline. Such a shrinkage might be expected to be accompanied by a diminution in the thickness of the narrower of the great outlet glaciers of the Victoria Land horst, which may well have been as much as 1500 feet. In the writers' opinion, glaciers from the Koettlitz and Newnes and Murray Valleys, forming the drainage of a Continental-Ice some hundreds of feet thicker than at present, would be quite sufficient to account for the flooding of confined bays such as McMurdo Sound and Robertson Bay. On the other hand, we agree with Debenham, that the height of the floating ice fringe of the continent may not have been much, if any, greater than at present, though in all probability its forward movement would have been much more rapid and its edge considerably farther north. Such moraines as those heaped up on the slopes of Mount Terror cannot, on this supposition, be explained except through the well-demonstrated power, which such swiftly moving sheets would have, of piling up to an unusual height against an opposing land mass. Even to-day, at Cape Crozier, great waves of pressure show in some degree what can be accomplished through this agency. The much greater outward thrust of the Barrier at the time of an ice maximum would readily account for the occurrence of erratics and whole moraines a thousand or more feet above the present glacier level.

No evidence whatever has been found of any inter-glacial period between this Pleistocene (?) maximum and the present day.

The fact that the large granite, dolerite and basalt erratics—in fact, all the rocks except the most resistant types—tend to be surrounded by *débris* derived from their own exfoliation, is proof of a somewhat considerable passage of time, measured by human standards, since they were deposited in their present position. That the recession of the ice has probably continued in geologically recent times is, however, indicated by a similar tendency to marked frost weathering, which is found in many boulders of the more recent moraines of the present glaciers which must have left their original positions *in situ* within historical times. Frost weathering acts incredibly quickly on some types of rock; it has very slow action upon others. Altogether, it seems likely that we are now viewing the downgrade of the same glacial cycle which was responsible for the production of the high-level moraines. The Robertson Bay evidence is sufficient to show that the deglacierisation takes place in steps with pauses of some duration in between. Signs of any marked amelioration of climate since the Pliocene are, however, entirely wanting. From physiographical evidence alone, it appears safe to conclude that no great amelioration of climate took place—at any rate, in South Victoria Land—in Pleistocene and recent times.

(*b*) *Raised Beaches.*

Before finally concluding this short review of the evidence on Antarctic climates in past ages, some consideration should be given to independent evidence of the recent

history of the continent as apart from that provided by moraines and erratics. Daly* has argued that "if the Antarctic ice-cap were thickened to the average amount of 700 feet, an average sinking of sea level to the extent of nearly 20 feet would be inevitab e." He has endeavoured to correlate recent raised beaches all over the world with an increase in volume of non-floating glaciers. If we examine the effect of such an Antarctic accumulation of ice on the level of the Antarctic lands themselves, we should expect quite a different effect. Arguing from the principle of the tendency of different sectors of the earth to maintain isostatic equilibrium, we should expect the loading of the Antarctic Continent with ice hundreds of feet in thickness to be accompanied by a depression which would more than counterbalance the opposite effect due to the withdrawal of water from the oceans to form icefields on this particular continent. Conversely, we should expect a corresponding elevation during most recent times, while the ice-capping was gradually being unloaded and the water was returning to its original position in the ocean basins. Evidence of the depression is likely to be lacking or clouded by other factors, though there is no doubt of there having been a very considerable subsidence along South Victoria Land since the formation of the present drainage system. Depths such as those opposite the Drygalski Ice-Tongue could not have been excavated with the continent at its present level. All the features of the South Victoria Land coast are those of a coastline of submergence. It is quite probable that this submergence may be, at least partly, correlated with the overloading of the continent with ice, which has taken place since Eocene times.†

Evidence of the most recent elevation, which should have accompanied the deglacierisation which has taken place since the last ice maximum, might be expected to survive to the present day to a considerable extent. What signs have been found of recent raised beaches, apart from the anomalous deposits of marine organisms, ocean-bottom material, and mirabilite, which in the opinion of the writers have been adequately explained by Debenham? Such evidence is of course somewhat obscured by the fact that the great Tertiary tectonic movements, particularly in South Victoria Land, may not even yet have ceased. There is, however, both in Graham Land and South Victoria Land, clear evidence of a recent uplift of a few feet which is of the order to be expected, if it is to be correlated with the stripping of the ice capping from the continent.

(*a*) *Graham Land.*

At three localities at or near Graham Land, Gunnar Andersson reports distinct evidence of recent emergence of the land. At Hope Bay, rounded pebbles are found at some distance above the present shoreline, and he considers that similar evidence of a yet further landward extension of the beach has been obliterated by the subsequent action of frost. At Cockburn Island, raised terraces exist up to 25 feet above sea level. At the Naze, in Sidney Herbert Sound, he records the existence of a bed of stratified

* 'Geol. Mag.,' 1920, p. 250.

† Recent changes in level in South Victoria Land will be discussed in the "Memoir on the Physiography of the 'Robertson Bay and Terra Nova Bay Areas,'" by R. E. Priestley.

clay 3 to 7 feet in thickness containing numerous marine organisms. An examination of the fauna causes its discoverer to come to the conclusion that the beach represents a recent elevation of at least 130 feet (40 metres). His description suggests a deposit in which floating ice played a large part, though the presence of a large gastropod, specimens of which were not secured, have led him to suggest the possibility that a milder climate than the present prevailed in Graham Land at the time. Quite large gastropods occur at the present time off the coast of South Victoria Land, however, and, in the absence of any dimensions of the one seen by him, the ice-borne boulders must be considered the dominant evidence of climate in this case. The possibility of this deposit being of the type attributed by Debenham to an entirely different cause must be borne in mind, but may, we think, be tentatively ruled out because of the thickness of the terrigenous portion of the bed. If it is a true raised beach, recent elevation up to 13 feet above sea level (the height of the bed) is proved. Hypothesis, based on the range of marine fauna contained in the beds, gives 130 feet as an outside limit, but it is extremely probable that the true figure is considerably less than this.* The stratified and uncontorted nature of the clay is strongly in favour of its having been laid down *in situ*.

(*b*) *South Victoria Land.*

Evidences of raised beaches in South Victoria Land are few and far between, but it should be remembered that by far the greater portion of the coast is ice-swathed. Also the presence of this ice, or even more ice, since the time when emergence set in would effectually prevent any coastal marine deposits, or even physiographical forms due to coastal marine erosion, from being formed except in peculiarly favourable localities.

In four regions along the 500 miles between McMurdo Sound and Robertson Bay beaches of some extent have been observed, and, in at least two of these, the position of the beach and other evidence as well clearly indicates a certain fall in sea level relative to the land.

(i) At the seaward end of the Dry Valley of the Taylor Glacier, one of the writers found a gradually sloping beach, in which numerous shells of Pecten Colbecki and Anatina elliptica and of Lima, together with other organic remains, such as the legs of Decapods and other crustacea, were embedded in considerable numbers up to 30 or 40 feet above sea level at least. The greater portion of the immediate surface deposit at this spot consisted of fine silt distributed by the thaw-water of the streams from glaciers further up the valley. Where these streams had cut down a few inches into the marine deposits of the beach, however, the fragments of marine organisms were numerous, and there can be no doubt at all that here, at the entrance to the Taylor Valley, a true recent elevation of the land has taken place. That

* Similar organisms of the present-day fauna have been found at certain depths only. From these facts an estimate of elevation may be made, but is not too reliable.

the elevation is a recent one was proved, both by the condition of the remains of some of the more easily decomposable organisms and by the similarity of the fauna to that at present inhabiting the shores of the Sound. The very existence of the marine organisms at this spot is proof that the elevation post-dates the latter stages of the retreat of the Taylor Glacier which formerly must have flooded the valley to a thickness of many hundreds of feet with ice.

(ii) Further up the coast at Cape Bernacchi, terraces occur which are strongly indicative of wave action and a recent emergence above the sea, while Dunlop Island a few miles further north appears to owe its existence above sea level to the same general elevation of the coastline.

(iii) A definite raised beach has been reported from Granite Harbour by Griffith Taylor, and is described by him in the Physiographical memoir. The elevation is of the same order as that inferred from the evidence described here in cases (i), (ii), (iv) and (v).

(iv) At Terra Nova Bay was seen the second example of a beach up to 80 feet above sea level. Here, recent emergence from the sea was proved by the absence of exfoliation on the granite boulders composing it. As at Hope Bay, the estimate is a conservative one, for the signs of wave action upon the higher boulders which were first exposed has been obliterated by the quick frost action most characteristic of the region. If further evidence of the emergence than the shape of the boulders is required, it is forthcoming in the occurrence on the beach of one or two boulders of kenyte, which could only have been brought from the McMurdo Sound area by free floating ice. No such rocks are to be found on any of the moraines of the hinterland, and it is practically certain that kenyte *in situ* does not exist in this area at all. The rock has only been found on the raised beach itself. The foreshore behind the beach is strewn with erratics derived from the ranges behind, and this again limits the age of the beach to the period subsequent to the last recession of the ice.

(v) The shingle beach at Cape Adare again affords evidence which, though unconvincing, adds some weight to the testimony in favour of the supposition of a small recent uplift. Though the beach could perhaps all have been formed at its present level in a milder climate, it is extremely unlikely that it was so formed under the present climatic conditions. The height of the rearward portions suggests a recent uplift of some few feet, and this is borne out by the presence of caves with exposed floors in the small bays which line the west coast of Robertson Bay.

Altogether, the existence of slight uplift in recent times all along the coast of South Victoria Land is we think proved. It is only reasonable that we should correlate this uplift with the most likely causative factor. The regions of uplift are not coincident

in area with the highest blocks of the faulted coastline, and, therefore, it appears likely that they cannot be adequately accounted for by recent block faulting or tilting movements. They are better coupled with the decrease in the thickness of the Continental-Ice with consequent readjustment of isostatic equilibrium common to the whole region. Along the greater portion of the coastline such a readjustment would necessarily leave no trace whatever.*

In using the Graham Land occurrence in support of his theory of world-wide shrinkage of oceans, in response to the formation of sheets of Continental-Ice, it appears to the writers that Daly has overlooked the phenomena peculiar to the loaded land masses as opposed to those unaffected by the ice accumulation. It appears to us much more likely to be part of a compensatory movement to counterbalance the undoubted deglacierisation which has taken place since Pleistocene times, than the result of a general lowering of sea level. The latter is a plausible, in fact it appears to be an inevitable, result of extraordinary glacierisation, but its local effects on the continents immediately affected by the ice-flood must, we think, be more than counterbalanced by the response to overloading.

Summary.

When reading recent papers on the climates of geological time, the writers have been particularly struck by the amount of evidence—particularly palæobotanical evidence—which has been adduced to show that zonal climate has probably been the exception rather than the rule in past geological ages.

Assuming that there has been no great wandering of the poles, it is to be expected that, in the Polar regions, the frigid phase of this zonal climate would leave evidence far transcending in degree that which might be expected from any other region of the earth. This is a fact which should be true with most of the main theories brought forward to account for the occurrence of glacial periods. In Table XIX, we show in tabular form that portion of the geological record, deposits belonging to which exist on or about the Antarctic Continent, together with a summary of the deductions regarding its climates we have been able to make from the sediments and the flora and fauna which they contain. The result, incomplete as the record is, is eloquent of the fact that, to all appearance, *glacial conditions have been the exception and not the rule in Antarctica.*

No evidence yet exists of either a Proterozoic or a Cambrian glaciation, though it must be admitted that the record is so incomplete that only very tentative conclusions can be drawn. Permo-Carboniferous glaciation in Australia, South Africa and India appears to be represented in the Antarctic only by a desert—possibly semi-frigid—climate with its appropriate deposits. Side by side with these desert sandstones, and intercalated with the arid periods and areas, we must recognise a widespread climate suitable for the development of a flora which gave rise by its decomposition to considerable beds of coal. Indeed, in those days, it appears that the Antarctic climate

* J. M. Wordie claims that the continental shelf is arranged in terraces.

Table XIX.

Geological Time Table.		Barrell's estimate of duration of Period.	Glacial Periods.	—	(In terms of Modern Zonal Climate.)
British.	American.	Millions of years.	—	Antarctic Deposits.	Climates indicated.
Recent ...	Recent ...	1–1·5	Yes	The Nazo raised beach, Graham Land	Frigid ...
Pleistocene ...	Pleistocene			Maximum extension of ice	Frigid ...
Pliocene ...	Pliocene ...	6–7·5		Pecten conglomerate of Cockburn Island	Frigid ...
Miocene ...	Miocene ...	12–14		Limestones of Campbell Island	Temperate(?) Tertiary Antarctic Ice-Age.
Oligocene ...	Oligocene ...	16		Volcanic Glacial Agglomerates	Frigid ...
				Tertiary Beds of Seymour Island	Sub-tropical to temperate
Eocene ...	Eocene ...	20–26		Moraine-like deposits of Graham Land (?)	First glaciation (?)
Cretaceous ...	Cretaceous...	40–50	(?)	Sandstones and shales of Seymour and Snow Hill Island	Temperate to warm temperate.
	Comanchean	25–35			
Jurassic ...	Jurassic ...	35–45		Slates and greywackés of Hope Bay	Sub-tropical to warm temperate.
Rhætic Triassic	Triassic ...	25–40		Beacon Sandstone...	Temperate to hot or cold desert. No definite evidence of glacial conditions, though strong evidence of seasonal climate.
Permian (Australian Permo-Carboniferous)	Permian ...	25–40	Yes		
Carboniferous	Pennsylvanian	35–50			
	Mississippian	45–50			
Devonian ...	Devonian ...	50		Shales of Granite Harbour...	Temperate (?).
Silurian ...	Silurian ...	40		Slates and greywackés of S. Orkneys	(?).
Ordovician ...	Ordovician	90–130			
Cambrian ...	Cambrian ...	70–110	(?) Yes	Archæocyathinæ Limestones	Warm temperate to tropical.
Pre-Cambrian	Kaweenawan			Marbles of New Harbour. Slate-greywacké of Robertson Bay. Graphite schists of Terra Nova Bay. Schists and gneisses	Warm temperate. (?) Indication of hot or cold desert conditions at Robertson Bay.
	Animikian				
	Huronian		Yes		
	Keewatin				
	Coutchichian				

was sufficiently salubrious to be the chosen home of a hardy flora which spread outwards to conquer the greater portion of the earth.

Now follows the mild almost tropical climate of the Jurassic Period, with its flora resembling the contemporaneous flora of Yorkshire at a time when the climate must have been much more genial than that of the present day.

Approximate uniformity appears to be the characteristic of the Jurassic flora from Pole to Pole and right round the earth, and the Antarctic continent was no exception to the rule. In the Cretaceous period, a general cooling does appear to set in. At first, frequent setbacks lead to considerable rises in the mean temperature, with long periods of temperate to subtropical climate. Little or nothing is known of the Antarctic climate during Eocene times.

In the upper Oligocene and lower Miocene, once more a temperate to subtropical flora holds sway over some portion of the Antarctic Continent. Towards the end of the Oligocene, the great tectonic disturbances took the outward form of cataclysmic eruptions, burying a great portion of the Antarctic Coastline beneath showers of *débris* of all sizes and shapes. Great outpourings of lava failed to have more than a temporary and strictly local effect on the continental temperature. How far, indeed, may the explosive eruptions of the Antarctic have contributed their quota to that veil of fine volcanic dust in the outer atmosphere to which is attributed by some scientists the general earth cooling which had its culmination in the Pleistocene Ice-age of world-wide extent? This is a question which we reserve for the more general discussion of the cause of glacial periods forming the second part of this chapter.

Already in Miocene times, the rapidly accumulating volcanic agglomerates and tuffs, both subaerial and submarine, were commencing to entomb the erratics which are the visible sign of the great cold forces which fought successfully against the local rise of temperature induced by the welling forth of lava flows. It is difficult to imagine the inferno of desolation which must have marked the battlefield of such gigantic forces. Certainly, the remains of the land flora and fauna of the continent must have disappeared amidst conditions closely approximating to, or even surpassing, the mediæval ideas of hell.

The question as to how far local or general ameliorations of climatic conditions took place in the middle days of this great Tertiary Antarctic Ice-age is not soluble with our present meagre knowledge. When, however, we approach nearer to recent history, we have reason to believe that, in the high level moraines of the Antarctic mainland and in the ice-gouged valleys of the sub-Antarctic islands, we are viewing the remaining evidence of the culmination of the Antarctic ice-floods which have since been slowly dwindling in size. Whether the Antarctic is approaching yet another interglacial period, or whether another long spell of quiescence is at last drawing near, we cannot say. Analogy with the beginning of the Ice-age with its climatic variations would suggest the possibility of yet another pulsation before the normal condition is reached. The earth is getting older and possibly, as Knowlton advocates,* the days of uniform climates have passed

* "Evolution of Geological Climates," F. H. Knowlton, 'Bull. Geol. Soc. Am.,' 1919.

with the passing of an unbroken cloud envelope from the atmosphere of the globe. All these are matters of speculation beyond the scope of the present section, which is concerned with the reconstruction of the Antarctic past from evidences existing in the present. There appears to be a strong case for the contention that a warm or temperate climate in the Antarctic has been the normal situation, broken once and again by lapses to a frigid climate which may have been brought about by any combination of a dozen causes, some of which are discussed in the following pages.

Knowlton's universal cloud envelope does not appear to be consistent with the frequent recurrence, both of Ice-ages, and of the desert climates with great temperature range, which appear to be the only possible agents to account for the strong evidences of mechanical weathering which recur again and again in the Antarctic record. Such climates appear to require the free outward radiation only consistent with a comparatively cloudless sky.

II.

In the first section of this chapter, has been discussed that evidence bearing upon the past climatic conditions in the Antarctic which can be gleaned from a study of the geological records of the rocks. The evidence, however incomplete, points to the fact that an explanation is required, not so much for the occurrence of previous glacial periods, as for the occurrence of periods when the polar continent was surrounded by warmer seas and was capable of supporting the growth of a heat-loving flora.

Before discussing the major long period fluctuations in climate evidenced by the geological record, it seems desirable to consider those variations which have occurred within historical times. The first part of this section will, therefore, deal with comparatively recent fluctuations in the degree of glacierisation, primarily in the Antarctic, and the corresponding variations in climate; the present climatic conditions of the Antarctic; and the evidence for the inter-relation of temperature, climate and other physical variables. The final portion of the chapter will discuss the theories which have been proposed as the cause of these variations.

1. Glacierisation in Recent Times.

The most complete data regarding the variations in the degree of glacierisation are, naturally, those relating to Europe, and an excellent statement of our present knowledge is given by C. E. P. Brooks.* Brooks deals with the period subsequent to about 25000 B.C., and traces the retreat of the glaciers of Northern Europe from that date, when Scandinavia was swamped by ice somewhat as the Antarctic Continent is now. This retreat was not, however, a continuous one, prolonged halts being indicated by the formation of large terminal moraines at times when the ice front remained stationary or

* 'Quart. Journ. Roy. Met. Soc.,' vol. 47, July, 1921.

nearly so. In the Alps, the glaciers also retreated, and here also the general tendency to retreat has been complicated by the superposition of minor variations.

The reconstruction given by Brooks is largely based on the work of G. de Geer.* In Scandinavia, the sinking of the land and the retreat of the ice edge were associated, and the time occupied in the retreat of the ice margin across the Baltic was about 8000 years. Thus, the edge lay on the southern shores of Sweden at about 10000 B.C. The retreat was stemmed, however, for some 200 years at about 8000 B.C., and the retreat then continued until 5000 B.C., when it was again stayed at Ragunda. The ice covering on Scandinavia had disappeared by 4000 B.C.

In the Alps, meanwhile, there were probably corresponding movements of retreat and temporary advance, the two latter of which seem to have been about 8000 B.C. and 5000 B.C. Brooks calculates that the elevation of land in the Alps, at the time of the last great glacial extension (about 25000 B.C.), was insufficient to account for the decrease of temperature necessary to lower the snow-line by the observed amount, and considers this resulted directly from the cooling effect of the contemporaneous sheet of Continental-Ice centred about Scandinavia.

A diagram in Brooks's paper, gives the supposed relationship between the extent of the Scandinavian ice-sheet and the position of the Alpine snow-line after 20000 B.C.

The changes experienced in North America clearly show that the retreat of the Continental-Ice was not a gradual one, but that, here also, there were irregularities in the retreat of the ice, which were probably not contemporaneous with those experienced in Northern Europe.

Brooks is clearly of opinion that the ice conditions are closely correlated with changes in geographical environment, and particularly with vertical movements, and that the irregularities in the rate of retreat are chiefly due to variations in height of the land masses.

From all regions, in fact, the evidence seems to show that the degree of glacierisation has decreased since 25000 B.C. Minor fluctuations have occurred and are occurring, but the present general tendency seems to be towards a continuance of the process of deglacierisation.

When we turn to the Antarctic, we see that there has been a similar tendency to deglacierisation. The evidence here is overwhelming and has already been given. As in the northern hemisphere, there appear to have been minor fluctuations in the rate of retreat, the best evidence for which is the occurrence of definite lateral moraines, as at Cape Adare, which must have corresponded in time with a cessation of the process of deglacierisation. The presence of many horizontal lying silt bands and blue bands, and the frequent occurrence of unconformities in the body of Antarctic glaciers, is equally evidence of changes in the amount of permanent snowfall, as pointed out elsewhere. Unfortunately, there are no data which might enable one accurately to calculate the date of the last maximum of glacierisation in the Antarctic, or the dates of the minor maxima and minima. It can hardly be doubted, however, that

* 'Ber. Internal. Geologenkongr.,' Stockholm, 1910.

the deglacierisation in the Antarctic has, roughly speaking, kept pace with that in the North Polar area.

When we consider the variations which have been observed in the Antarctic in historical times, or which can be inferred, it is necessary to remember that the seaborne glaciers and the Land-Ice formations will not necessarily decrease or increase in unison, since the chief forces of denudation are different in the two cases, while the conditions of precipitation may also differ widely.

Clearly, also, an estimate of the trend and fluctuations in the degree of glacierisation of the Antarctic Continent must take due account of the fact that adjacent areas, at the present day, sometimes show the most extraordinary differences. Examples of this differentiation have already been given, such as the difference between the east and west sides of Robertson Bay and the difference between the Butter Point Piedmont-Ice and the Dry Valley area, only a few miles further north. Even in Dry Valley itself, indeed, there is a clear differentiation between the degree of glacierisation within the valley and on the uplands bordering the valley, as is evidenced by the present extension of small glaciers such as the Suess, the Canada and the Commonwealth Glaciers, into the dry bed of the once mighty Taylor Glacier.

As will be seen later, the diversity of successive seasons is also such as to render it even more difficult to obtain a just appreciation of the course of recent events, but a circumstance which makes such an appreciation more easy is the undoubted fact that large ice-formations will generally show only the general trend of the glacierisation, while small glaciers of local extent and small size, including glaciers of the snowdrift type, will indicate the short-period variations with which we are now concerned. Clearly, under present Antarctic conditions, any evidence for a decrease in glacierisation in such small glaciers, will be best shown by a retreat of the glacier face, while evidence for an increase of glacierisation will be most clearly shown on the surface of the glacier, or in a vertical section of the glacier.

South Victoria Land is likely to afford by far the most satisfactory evidence, since it has been under direct observation since 1840, and an examination of the records of the Expeditions at once shows definite indications of a measurable decrease of the ice covering of this portion of the Antarctic mainland, which has taken place within this short space of time.

(*a*) The early accounts of Ross Island in 1841, when compared with those of the recent Expeditions, certainly suggest a considerable dwindling of the local ice-caps of the volcanic peaks which form the high land upon it. This might perhaps plausibly be attributed to unusual snowfall and calm weather before Ross's advent. Taken in conjunction with the other proofs that follow, however, it is more likely to be a correct indication of decreasing glacierisation in the present.

(*b*) Ross, when sailing along the Ross Barrier in the "Erebus," charted the position of its seaward cliff. This ice formation has retreated an average of some 25 miles between that date and the "Discovery" Expedition, when it was carefully re-charted in 1902. Since that date, other slight alterations in the face have taken

place, and these are shown in the chart of the Ross Barrier included with this memoir. (Map II.)

(c) The ice of the various Piedmont-Ice sheets, along the coast between Mount Discovery and Mount Melbourne, is undoubtedly in retreat. In 1902, while sailing along the coast, Scott charted Depôt Island as connected with the mainland by Piedmont-Ice. In 1908, David found this and a neighbouring island behind it to be surrounded by sea ice. On the same journey in 1908, David and Mawson charted the point called by them Gregory Point as a cape. In 1912, the Northern Party of the Scott Expedition found this point to be an island separated from the mainland by a strait of sea ice. Tripp Island was also charted by the Magnetic Pole Party of the Shackleton Expedition in 1908, as lying close to the Piedmont-Ice; in 1912, it was farther removed.

Some of these alterations might conceivably be due to errors of observation, but this cannot be the case in all. There appears to be no doubt that, all along this coast, the coastal fringe of land-ice is breaking back, in places some hundreds of feet in a year, though the average retreat must be much less. It would be interesting to know how far a similar retreat of the coastal fringe of land-ice off Wilkes and Adélie Land is responsible for the discrepancies found between the accounts of the earlier and the later explorers.

(d) The breaking back of the Erebus Bay Ice-Tongue (Glacier Tongue) in McMurdo Sound may be another indication of the same progressive tendency towards deglacierisation, but judgment on this point is best suspended until further observations have shown whether or not this loss is made good in the immediate future by the advance of the tongue.

The above evidence refers to variations in the aspect of large ice-formations, and seems to be conclusive proof that:—

(1) The deglacierisation of the Antarctic Continent is still in progress, apart from minor fluctuations, which will not be evidenced in ice-formations of this size.

(2) The deglacierisation of the seaborne ice-formations has proceeded at a much quicker rate. This can only be due to an increase in the sea temperature.

Evidence of short period fluctuations, obtained from the examination of small ice-formations, is much less clear. Such evidence is, naturally, best shown in the small masses of Snowdrift-Ice which have little or no movement, since the result of movement may be to carry a portion of a glacier from an area where denudation exceeds deposition, into an area where the reverse is true. Such contrasted results often obtain side by side on the same glacier, due to the excessive deposition of drift snow on the lee side of all the higher portions of the glacier surface. Many of the unconformable deposits of snow, or nèvé, upon layers of true ice on such glaciers can be traced to such causes, as is the case on the Barne Glacier, whose terminal face is definitely in retreat. The latter is also true of the small glaciers examined on the western side of McMurdo Sound, which line the left bank of the Koettlitz Glacier. On the other hand, some of the small glaciers

on the sides of the Taylor Dry Valley do not show definite evidence of retreat on their terminal faces. Further north, along the same coast, the evidence of such glaciers sometimes indicates a process of retreat, sometimes not.

It is when we come to examine vertical sections of such small glaciers that one is struck with the fact that many of the nearly horizontal silt bands and blue bands cannot be adequately explained, except by the assumption that there have been definite fluctuations in the amount of the difference—deposition less denudation. As explained in another chapter, a period of unusual warmth with much formation of water will result in the formation of bubble-free ice on the glacier surface, and the vertical distance between two such bands of clear ice will represent the residual permanent deposit between two such periods. To some extent, the same is true of certain of the silt-bands. Unfortunately, it is not possible to draw any deductions regarding the periodicity of the climatic fluctuations causing these results, without more detailed observations than have been made by us. We would, however, suggest the importance of making such detailed observations, and, particularly, of attempting to measure the radioactivity of the ice in a vertical ice section at a large number of depths. Observations of this nature might well yield results of considerable importance.

Our own observations, it is clear, do not give definite evidence of anything except the occurrence of short-period fluctuations in the permanent deposit, and do not enable us to say whether these fluctuations are of constant periodicity, or not. Neither do they enable us to add anything definite as to the present tendency, whether towards deglacierisation, or the reverse.

The evidence from an examination of small snowdrifts is, however, precise in the following respect. It has already been pointed out that the permanent drifts formed in the lee of small projections very quickly grow to their full dimensions in the stormy winter season, and it may be taken as certain that, each winter, these small snow-drifts will grow to their maximum size, in conditions which approximate at all closely to those obtaining at the present day. The presence of silt-bands low down in the ice of such a snowdrift can only then be explained as the result of periods when denudation was greater than at present. In the case of the drift at Cape Evans, in which the magnetic and pendulum caves were excavated, the occurrence of penguin feathers close to and on the ground is proof positive of the prevalence of such conditions in the not far-distant past. The evidence which is available does not, however, enable us to say definitely that denudation in the summer months is now decreasing, though there is every probability that this is the case, nor does it tell us anything whatever regarding the tendency to increase of deposition, or the reverse.

On the whole, the evidence suggests that, *at the present time*, the sea is becoming warmer; the denudation is probably becoming less *in the summer months*; and the annual value of deposition less denudation on Land Ice-formations is decreasing, in South Victoria Land. It is not possible to separate the short period fluctuations from

the general trend towards deglacierisation, which is presumably still effective and which operates over the whole Antarctic Continent.

It should be pointed out that, if Debenham has given the correct explanation* for the occurrence of iceborne deposits of sponges, shells and mirabilite, this is evidence of a colder sea temperature some time in the recent past, at which time the sea temperature was sufficiently low to permit significant amounts of ice to be formed from the sea water and to be added permanently to the under surface of floating ice in certain favoured localities.

On his explanation, the occurrence of the deposits on a floating ice-sheet such as the seaward end of the Koettlitz Glacier demands a nicely balanced relation (after their first inclusion in the body of the ice) between the denudation of the upper surface, which undoubtedly obtains at present, and the denudation at the ice-water interface which is also undoubtedly taking place to-day. If the latter action were too quick, or the former too slow, the deposit would necessarily appear, not at the upper surface, but at the lower.

2. Climate in Historical Times.

When we come to consider the climatic conditions of Europe which were associated with the retreat of the last great continental ice-sheet over Scandinavia, we are forced to agree with Brooks that these were, at any point, largely governed by the distance from the ice-sheet and from the "glacial" anticyclone formed over it. A further complication is, however, introduced in North Europe by the supposed variations in height which closed and opened the Baltic to the waters of the neighbouring seas.

These variations in height have continued, moreover, since the Continental-Ice disappeared. Brooks correlates the rise of Denmark and the closing of this outlet of the Baltic with the inception of the "Continental Phase" about 6000 B.C., when the variation of temperature between summer and winter was large and the climate was of continental type. This was followed by the "Maritime Phase" in 4000 B.C., due to the reopening of the Baltic to the waters of the North Sea, which was associated with low annual temperature range and an increase in rainfall.

By 3000 B.C. an elevation had taken place, resulting in the initiation of drier conditions—the "Forest Phase."

By 1000 B.C., the climate had become more humid and extensive peat beds were laid down at this time. According to Huntington,† the climate of California was also moister between 1000 B.C. and A.D. 200, and this may also be true for the countries bordering the Mediterranean between 400 B.C. and A.D. 200.

This "peat-bog phase" is considered to terminate about A.D. 300. Since that time, conditions in Europe have been generally as at present, but there is evidence of colder winters than at present in the ninth to the thirteenth centuries, when the Baltic froze in winter. At the same time, there seems to have been a greater rainfall during

* *Loc. cit.*

† Carnegie Institution, 1914.

this period in Arabia and North Africa. Since 1325, the height of water in Lake Mexico has generally declined, and there seems every possibility that this desiccation in low latitudes is more or less general, and is associated with the decrease in the ice masses in high latitudes.

No information regarding the recent climate in the Antarctic is available, except the very indirect evidence, already quoted, which is derived from glaciological investigations.

The most valuable evidence is clearly that of the decrease in extent of the Ross Barrier, which can only be adequately explained on the view that the Ross Sea temperature has been rising. This does not, however, mean that the air temperature has necessarily also risen. The increase is probably due to a greater interchange of water between high and low latitudes. It is, however, quite possible that the increase in sea temperature, if due to increased interchange of sea water, would be associated with increased Antarctic air temperature due to increased exchange of air between the Antarctic Continent and lower latitudes. No evidence is, however, available on this point.

It is clear, in fact, that such evidence as is available regarding the variations of climate in different parts of the earth, points to the fact that this is dependent very largely upon local factors, and also upon the geographical conditions in the whole hemisphere.

3. The Present Climate of the Antarctic.

In preceding chapters, it has been made clear that the climate of the Antarctic varies greatly from year to year and from place to place. In large part, the variations from place to place can clearly be traced as due to special topography, modifying the general Antarctic conditions. The large variations in climate from year to year are, however, less easy of explanation, but must, we think, be associated chiefly with the distribution of ice and water on the fringe of the continent. The differences which have been observed in different years, clearly owe their origin to variations which are of a catastrophic nature. Thus, the great difference between the winter of 1912 and previous winters, in McMurdo Sound, in the temperature and mean wind velocity, was almost certainly associated with the absence of sea ice during 1912. Normally the sea of McMurdo Sound freezes early in the spring and, at first sight, we would be tempted to say that the probability of this strait becoming covered with Fast-Ice would be greater, the later in the season it remained open. This is not the case, however. Unless the Sound freezes early, before the advent of winter establishes the large horizontal temperature gradient between sea and land ice, the high winds caused by this temperature gradient favour rather the retention of existing conditions and are strongly against the freezing of the Sound late in the winter. We see, therefore, that the climatic conditions of the autumn months—March and April—are, in McMurdo Sound, those which decide the winter conditions in this region. It is circumstances of similar nature which cause the large differences between the climate in any one region, from one year to another.

The actual meteorological data relating to the climate of the Antarctic, so far as known, are given by Simpson*, and the reader is referred to the meteorological volumes of the Expedition for this detailed information.

Taking the Antarctic Continent as a whole, and allowing, so far as possible, for the variability of the climate from year to year and from place to place, it seems clear that one can designate the prime cause of the present Antarctic climate, to be the "glacial" anticyclone which lies everywhere on and over the continent, and which is clearly associated with the high elevated dome of ice which swamps the topographical features of by far the greater portion of the land.

There is a general outflow of air from the interior of the continent with an easterly component due to the earth's rotation, and the wind generally tends to flow down the line of greatest slope at each point.

Whether Hobbs is correct in stating that the air circulation results from the cooling of the air in contact with the elevated snow surface, or whether our contention is correct that the cause of the circulation lies in the horizontal temperature gradient at the edge of the continent, and that the elevated dome of ice and snow results therefrom, is of no importance to the present argument. Whatever may be the prime cause of the outward blowing winds from elevated snow surfaces such as Greenland and the Antarctic, one can hardly doubt that this cause is associated with the properties of a snow surface, such as low thermal capacity and conductivity, and high reflecting power, and that the circulation on such a snow-covered mass is greatly different from that which would obtain over a land mass of equal height and size which is not swamped with snow.

One is in fact led to the conclusion that the initiation of a complete snow covering on a previously bare elevated landmass will profoundly modify the existing air circulation, so as to cause a circulation leading to the formation of a dome-shaped covering such as that observed.†

This elevated snow-covered dome receives, in winter, no direct radiation from the sun while, in summer, the radiation received is very considerable but does not vary largely during the course of 24 hours in high latitudes. On the other hand, radiation from the earth is very great, partly owing to the poverty of water vapour in the cold atmosphere over the elevated continent.

The low thermal conductivity, low specific heat (in comparison with water) and the high coefficient of reflection together make for large temperature variations of the snow surface and the air in contact with it, as the radiation from the sun varies during the day in spring and autumn. So pronounced is this effect that the curve representing the march of the mean daily temperature throughout the seasons lags almost inappreciably behind the curve representing the variation in radiation from the sun, while the maximum daily temperature range is comparable with that observed at continental stations near the Equator, notwithstanding the much greater difference

* 'British Antarctic ("Terra Nova") Expedition,' "Meteorology," vol. 1.

† As pointed out before, the probability exists that the increased wind velocity and low percentage humidity associated with excessive snow slopes is the cause of the icy covering of the upper portion of the steeper glaciers.

between the maximum and minimum zenith distance of the sun during the day in the two cases.

Rough estimates of the amount of yearly precipitation and denudation have already been made in previous Chapters. Both are small in amount. The factor—precipitation less evaporation—seems to be very small but positive on the top of the plateau; to be negative on the great valley glaciers leading up to the plateau, except in the lower reaches; to be again positive but of small amount on such ice formations as the Ross Barrier,* which lies nearly at sea level. There is some evidence that the precipitation is greater at lower latitudes, where the denudation is also greater, and this is certainly the case over and near the open sea, as is evidenced by the comparatively heavy snowfall observed on Pack Ice formed in the open sea.

A distinction must clearly be drawn between summer and winter conditions in the Antarctic. When it is remembered that the radiation received and emitted by the earth in high latitudes varies little during the whole 24 hours, except in the spring and autumn months, it is clear that some such distinction should be drawn. In the winter months, radiation from the sun is inappreciable, while radiation from the earth is apparently very intense. Winter is therefore, the type of an extreme condition such as would obtain when the earth's atmosphere was extremely dusty, while summer conditions are those which approximate most closely to conditions of little atmospheric absorption of the sun's rays. The radiation contrast between pole and equator is least in summer and greatest in winter. This, in itself, might suggest that winter, the stormier season, should have the greatest snowfall, whereas the reverse is true. The higher temperature associated with the Antarctic summer results in greater snowfall in that season while, at the same time, it causes better "packing" of the snow, so that the less intense winds are not so effective, in sweeping the snow from its position, as in the colder months.

One other point, which is discussed in greater detail elsewhere, is that high temperature and high wind velocity are very generally associated in the Antarctic. The reason for this circumstance has been given by Simpson.† One need only say that this association is generally true in all localities and in different years, provided that the same seasons are chosen for comparison in each case. The reason for this restriction is the fact that winter and summer climatic conditions are governed by totally different factors, the winter being by far the stormier season, at least at the edge of the continent.

The relation between climate and the degree of glacierisation of the Antarctic has long been the cause of controversy. Captain Scott, it is believed, was the first to suggest that an increase in the temperature of the Antarctic would result in an increase in the degree of glacierisation. This argument was based largely on the following facts:—(i) The known greater precipitation on the continent in the warmer months

* 7½ inches of water yearly.

† *Loc. cit.*

of the year, and (ii) the fact that such islands as Bouvet Island show very intense glacierisation, notwithstanding the much higher mean annual temperature. Neither argument, however, can carry great weight, in view of the great difference between summer and winter conditions and the difference in climatic factors, other than temperature, between islands such as that named and the Antarctic Continent.

Temperature alone cannot be the deciding factor and to obtain a just estimate of the effect of climate in a given position involves a discussion of all the meteorological data. Nordenskjöld* has already pointed out the very great importance of wind in this problem, and it is quite clear that its importance can hardly be over-estimated when the temperature is so low that the snow-flakes and crystals are small and unable to cohere, or grow quickly into larger aggregates, on the snow surface. This is, no doubt, one reason why the permanent additions to the snow surface are so slight in the winter months. On the other hand, the snowfall in winter is definitely less than that in the warmer months, and this has been observed by all Antarctic expeditions.

In a previous chapter, emphasis has been laid on the fact that the largest types of expanded foot glaciers are best developed in Alaska and in the Antarctic. The former area is one of heavy precipitation and heavy denudation. In the latter area, both precipitation and denudation are slight. It cannot, in fact, be too clearly emphasised that a great precipitation at comparatively high temperatures may result in glaciological conditions very similar to those due to a small precipitation, associated with an even smaller denudation at much lower temperatures. It is the difference between precipitation and denudation which is effective (not the absolute magnitude of either) in deciding the degree of glacierisation. We believe that small precipitation and small denudation are associated with glacierisation of the Continental type in Polar regions, and that precipitation and denudation are both great for ice masses such as those formed in temperate regions and those which are surrounded by sea (Island-Ice formations). The initiation and growth of an ice-formation probably demands a heavy precipitation of snow; the maintenance of an ice-formation requires less precipitation, though this must still be in excess of denudation. This leads to the view that the initiation of an ice mass may be associated either with a decrease of temperature (due, say, to rise of land), or to a more vigorous circulation in an area which has already a temperature sufficiently low to permit the formation of glaciers, were the precipitation greater or the denudation less.

4. Periodic Variations in the Climate of the Earth.

Up to this point, no mention has been made of the periodic character of climatic variations since historical records commenced. In view of the comparatively short range of years which can be studied, it is clear that only those variations which have a short period can be definitely established, and linked in association with physical factors for which records are available.

* *Loc. cit.*

Sunspots and Climate.—A useful summary of the data relating to the connection between sunspots and weather has been given by Brooks.* According to him, there is a definite correspondence between the 11-year sunspot period and weather, in such a direction that, at sunspot maximum, the atmospheric circulation is most intense as a result of "a deepening of the lows, *i.e.* greater storminess, and an intensification of the highs." There is also evidence that the storm tracks in America shift southward at sunspot maximum and that the absolute storminess increases at the same period.

Clearly, in these circumstances, one would expect to find a close correspondence in period between temperature and sunspot area, and this is indeed the case, the temperature being generally low at sunspot maximum and high at sunspot minimum. There is also evidence that the mean daily range, in the tropics, is less at sunspot maximum.

Sunspots and Radiation from the Sun.—Humphreys† has discussed in some detail the relationship between mean annual air temperature, sunspot numbers, and the intensity of radiation received from the sun on the earth's surface.

He quotes figures showing the relationship between the temperature at selected stations and the pyrheliometric values, and it is seen that a general correlation between the two does exist, decreased temperature being associated with decreased radiation from the sun. Moreover, it has been proved that, in a general sense, temperature and sunspot frequency are associated, increased sunspot frequency corresponding to decreased temperature. Finally, it is known that a combination of the sunspot frequency curve and the pyrheliometric curve represents with considerable faithfulness the mean temperature curve on certain portions of the earth. A very good case has also been made out to show that the discrepancies between temperature and sunspot frequency curves may be due to variations in the amount of dust in the earth's atmosphere, chiefly to volcanic dust projected in volcanic explosions such as that of Krakatoa. It is important to note, however, that the facts do not warrant the deduction that increased sunspot activity is associated with a decreased mean temperature *all over the earth*, and it is quite possible that in one portion of the earth increased sunspot activity will be associated with decreased temperature, and in another spot with increased temperature.

One explanation for the observed decrease in temperature with increased sunspot activity is offered by Blanford's theory, which supposes that this inverted effect results from greater evaporation over the water areas of the earth, causing greater cloudiness, greater rainfall and decreased temperatures. Humphreys suggests the cause may lie in the increased formation of ozone in the upper atmosphere, due to increase in the amount of ultra-violet radiation from sunspots.

Analysis of the Chinese Earthquake and Sunspot Records.

H. H. Turner‡ has recently analysed the Chinese records dealing with earthquakes and sunspots, and has compared the periodicities found with those of the Nile records

* 'The Meteorological Magazine,' June, 1921.

† 'Physics of the Air.'

‡ 'Monthly Notices,' Roy. Ast. Soc.

and the records of tree growth. The longest period which can be established from records of this duration is that of about 270 years, which is evident in all these records. Prof. Turner also discusses the possibility that this periodicity may be identical with the long period term in the moon's longitude.

Mention should also be made of Petterssen's theory* of the relation between climate and "tide-generating force," which demands periodicities of about 9 years, 90 years, and 1800 years. Petterssen's maxima of tide-generating force fell in 350 B.C. and A.D. 1434, with minima at 1200 B.C. and A.D. 530, so far as the 1800-year period is concerned. It is claimed that there is evidence of a quiet stable climate in Northern Europe at these times of minima, and of great storminess and severe climate at the times of maxima.

The equivalence in period shown to exist between climate and temperature, sunspots, tree-growth, Nile records, earthquakes and possibly the long period term of the moon's longitude, clearly indicates that a definite relationship exists between them. Variations in radiation from the sun may be the cause of the climatic variations on the earth; equally, these variations on the sun may be themselves due to interactions between the different units of the solar system. In any case, the amount of radiation received from the sun by the earth must have a notable effect on the climate of the latter. Such variations in the amount of received radiation cannot be due entirely to variations in the absorptive power of the earth's atmosphere, due, for instance, to variation in the amount of suspended dust. It seems most probable that the amount of heat radiated by the sun is a maximum at sunspot maxima and that, superimposed on the original variations, are others due to variable absorption in space, in the sun's, or in the earth's atmosphere. It is probable, for instance, that the area of the polar caps of Mars varies with the number of sunspots and that the area is greatest at sunspot minima.†

A varying absorption of the sun's rays in the earth's atmosphere may be due to one or more of several causes—variations in the amount of water vapour, of water clouds, of the gaseous constituents of the atmosphere, and of volcanic dust, or dust derived from sources other than the earth. The variation in atmospheric absorption may, or may not, have the same periodicities as the radiation emitted by the sun.

The climate of the earth is, however, also affected by the amount of radiation from the earth into space, and therefore by absorption in the atmosphere of the earth's long wave radiation. Generally speaking, the earth as a whole will be warmed or cooled according as the radiation from the sun to the earth or from the earth is greater. Thus cooling may take place if the absorbing substance in the atmosphere is in fragments large in comparison with the wave length of the maximum energy radiated from the sun, and small in comparison with the wave-length of the maximum of the energy radiated from the earth. Such a cooling would result from the projection of sufficient volcanic dust into the earth's atmosphere. Such changes might also result from differences

* 'Svenska Hydrogr.—Brol. Konim. Skrifter,' H.5.

† Antoniadi, 'Monthly Notices,' Roy. Ast. Soc., June, 1916.

in the amount of the gaseous constituents of the atmosphere, as water vapour or CO_2, which are more absorbent of the long wave radiation from the earth, so that an increase in the amount of water vapour would result in a warming of the earth. Another way in which the radiation from the earth may be affected is by the chemical action of the radiation of the sun and the formation of a substance (such as the formation of ozone by ultra-violet radiation) which is more strongly absorptive of radiation from the earth. That such an effect occurs at high levels, but not at low levels, seems to be indicated by Lord Rayleigh's experiments on the absorption of ultra-violet radiation.*

Humphreys suggests† that the increased auroral activity at times of maximum sunspot activity may result in the production of hygroscopic compounds causing cloud formation. The radiation contrast between the Antarctic and the equatorial regions, if this effect did take place, would be likely to be peculiarly effective, owing to the fact that the aurora is chiefly confined to the Polar regions. Lindemann‡ has lately demonstrated the possibility that the earth, at least in Polar regions, may be continually bombarded by charged particles projected *in clouds* from the sun, these particles causing the aurora, on reaching a certain depth in the earth's atmosphere. It does not appear likely, however, that any substance with much greater *selective* absorption in the visible than in the infra-red region would be so projected into the Polar regions and notably affect the radiative conditions in the Antarctic. If, however, such a state of affairs existed, or if larger particles could be so projected, they would arrive in greatest number at times of sunspot maxima, and when the solar latitude of the sunspots was most favourable to such a projection towards the earth.

The theory of Lindemann has been strengthened by the work of Megh Nad Saha§ who has applied the "Reaction-Isobar" to calculations of the ionization in the sun's atmosphere and has accounted for the absence of the enhanced lines of certain elements below definite levels of the chromosphere. If, now, selective light pressure is the mechanism driving these elements outwards against the sun's gravitational field, the possibility exists that certain elements may be projected continually from the sun, to reach the earth's atmosphere, in amount which is greatest at times of sunspot maximum.

It is not difficult to see that variations in the amount of radiation reaching the earth will result in climatic variations of the same period, through their effect on the great centres of action of the earth, intensifying or reducing in strength the great permanent glacial anti-cyclones. It is also easy to see that such variations in radiation will result in corresponding variations in the amount of landborne ice in Polar regions. The latter variations will result in variations of the gravitational constant, thus upsetting the isostatic equilibrium of the earth. These may be of sufficient amount to cause the associated periodicity of earthquakes and the long period term in the moon's longitude.

* 'Nature,' July 8, 1920.

† *Loc. cit.*, p. 92.

‡ 'Phil. Mag.,' December, 1919.

§ 'Phil. Mag.,' December, 1920. 'Proc. Roy. Soc.,' May, 1921.

It seems to us likely that the ultimate cause lies in the interaction of the sun and his planets, the "gravitational field"* of the sun varying with periodicities determined by these interactions, causing variations in the sunspot activity of the sun and in the radiation to the earth. This radiation, after absorption in the atmosphere of the sun and the earth causes periodic variations in the earth's climate—temperature, rainfall, etc.—which are probably not in the same phase at all parts of the earth, maximum air temperature at one place, corresponding to minimum at another. In the meantime, the change in the sun's "gravitational field" must be associated with changes of the same period in the "gravitational field"† of the earth and the moon, resulting in variations such as the long period term of the moon's longitude, and in a variation of equal periodicity in the occurrence of earthquakes, and of earth movements.

The principle of isostatic compensation, as Hayford and others have shown, is substantiated in that a *tendency* towards compensation has been shown to hold over large areas of the earth's surface; complete compensation may exist in places. In our opinion, the excess or deficiencies from complete compensation must be interpreted as a pre-disposition to movement of the land surface in a vertical direction and to the occurrence of earthquakes.‡

A clear relationship between earthquakes and tree growth, together with Nile floods, is not difficult to understand, if we can assume, as seems reasonable, that earthquakes are associated with volcanic activity in their dependence upon variations of the earth's "gravitational field," and can agree with Humphreys that the amount of volcanic dust in the earth's atmosphere has an unmistakable effect upon climate. Such variations in the earth's "gravitational field" may also result directly from variations in the amount of radiation from the sun, operating through the waxing and waning of ice on the land in Polar Regions.

On this view, the periodic variations in climate are due partly to variations in the radiation received from the sun and partly to causes associated with variations in the

* Phenomena of a tidal nature on the sun are associated with variations of the sun's "gravitational field" according to the meaning attached here and subsequently to these words.

† This term is intended here to include any variations due to the attraction of the planets, and therefore includes forces of a tidal nature.

‡ In the Report on the gravitational observations of the Expedition, of this series of memoirs, a discrepancy is observed between the value of "g" found at Melbourne and that previously observed. The evidence for a real difference is unreliable, but should be mentioned as bearing on this point. Moreover, the sudden changes observed in the rates of astronomical clocks do suggest the possibility of corresponding sudden changes in the gravitational constant. Such changes are discussed by Sampson in 'Monthly Notices,' Roy. Ast. Soc., January, 1922. MM. Philippot and Moreau, in the same volume, state—*Les comparaisons fréquentes de nos pendules modernes avec l'horloge celeste nous feront peut-être douter un jour de la régularité de la rotation de la terre. Serait-il téméraire de supposer que des variations de la pesanteur—en direction et en intensité—et les petits secousses sismiques modifient les marches des horloges?*

Attention is drawn in Publication No. 10, United States Coast and Geodetic Survey, to the fact that large anomalies in the value of "g" are found on the Pacific coast of the United States. Here, the activity of recent mountain formation is accompanied by increased elevation as a rule, and the area is subject to frequent and severe earthquakes.

sun's and earth's "gravitational fields." Both variations have a common cause in the interaction of the sun and the planets and are of the same periods, though their modes of operation are different. Both modes of operation seem to be dependent partly on the occurrence of catastrophic changes—the formation of sunspots on the sun and the vertical movements and outbursts of volcanic activity on the earth. These will result in climatic variations whose period and amplitude are very variable and it will therefore require long periods of time to establish their average periods and amplitudes.

As regards the conditions operating at the present day, Brooks has shown that the sunspot numbers have shown a steady decline since 1870. This is in conformity with Brown's analysis.* Since Ross's time, the Barrier has suffered a notable loss at its seaward edge which, it seems to us, must be ascribed to an increase in the sea temperature in the Ross Sea during that period, which, however, does not necessarily mean an increase in *world* temperature. The moon had reached its maximum displacement in 1790. The last earthquake maximum, according to Turner†, was about 1800, slightly preceded by a maximum for tree growth. As pointed out by Turner,† when considering a possible relationship between earthquakes and the long period term in the moon's longitude, "the moon's longitude was apparently increasing in 1720 and decreasing in 1860, or the day was long in 1720 and short in 1860. Thus the radius of the earth was largest in 1720, and shrinking from 1720 to 1860, when it would be smallest." It is in this period that the Chinese earthquake maximum falls. Further, the earthquake maximum is spread over a period of about 60 years followed by quiescent periods of about 210 years—precisely what we would expect if its cause was due to a change in the earth's gravitational field operating only on one side of the maximum. Judged by these standards, the sunspot activity is now decreasing, as well as earthquake activity ; the atmosphere should be comparatively free from volcanic dust, the world temperature probably increasing, the "storminess" decreasing and the temperature contrast between Pole and Equator diminishing, with decreasing snowfall in the Antarctic as a result. There is nothing in the Antarctic records of historical times which appears to contradict these surmises, so far as glaciological observations are concerned, in view of the historically recent greater extension of seaborne and small land glaciers.‡ As pointed out previously, large land glaciers are not likely to show clear evidence of climatic variations of such short period as the one under consideration.

Of the direct causes which have been suggested for the initiation of glacial cycles, one of the most interesting is the variation in radiation received on the earth from the

* 'Monthly Notices,' Roy. Ast. Soc. Vol. LX. p. 600.

† Turner, 'Monthly Notices,' Roy. Ast. Soc., May, 1919.

‡ Unless the increase in Ross Sea temperatures, which has caused the recent retreat of the Ross Barrier, cannot be reconciled with a period of decreasing storminess. There is some evidence that the sea temperatures in McMurdo Sound were higher in the winter of 1912 than in the previous less stormy winter. On the other hand, the years covered by the "Discovery" Expedition, when the "Discovery" remained frozen in at Hut Point, were years of cold calm weather.

sun, due to variations in the dustiness of the earth's atmosphere. There is distinct evidence that rise of land has been associated in the past with glacial epochs, and it seems reasonable to suppose (as Humphreys has shown) that rise of land, and volcanic activity which can lead to the continued projection of volcanic dust into the earth's atmosphere, are not unconnected. On this assumption, we will first examine, so far as possible, the results of such a continued projection of volcanic dust and see where the hypothesis leads us, when applied to Antarctic conditions as they are at present.

The first obvious result of a formation of volcanic dust in this way leads, as Humphreys shows, to a general lowering of temperature over the earth, due to the greater absorptive power of the dust for sunlight than for radiation from the earth. In the Antarctic, owing to the low altitude of the sun and the consequent longer path of the sun's rays through the upper atmosphere, the radiation from the sun will be decreased more than will be the case in Equatorial regions, *i.e.* the radiation contrast between Pole and Equator will be increased, with more active atmospheric circulation and greater wind velocity in the Antarctic. It might, at first sight, seem that the correspondingly greater decrease in radiation from the sun in Polar regions would involve a temperature decrease in the Antarctic, but this does not seem to be a necessary condition, nor, on consideration, does this seem a probable outcome of an increased atmospheric circulation. As substantiation of this, we find that much the most stormy winter in the Ross Sea area was that of 1912, which was also much the warmest. As Simpson has shown, the conditions on the snow surface of the Ross Barrier are such as lead to the formation of inverted vertical temperature gradients, and the temperature difference between Ross Barrier and Ross Sea causes southerly winds, which (when they rise to blizzard force) result in a complete mixing of the lower atmosphere and a great rise in surface temperature. The mean surface temperature is, in fact, conditioned by the number of blizzards, and the mean temperature is higher, the higher and more frequent the winds.

As stated in previous chapters, by far the greater part of the snow falls during high winds, even though high winds in themselves lead to great ablation, both by evaporation and by drift chiselling of the snow surface. In conformity with this, observation showed that the quantity—deposition less ablation—was much greater in the winter of 1912 than in the preceding less stormy winter. The argument leads to the conclusion that, in the winter at least, and probably also in the warmer months when the greater part of the snowfall takes place, increased temperature contrast between Pole and Equator, due, for instance, to volcanic dust, will be associated with a greater permanent addition of snow to the surface in the Antarctic.

For the Barrier, at least, the argument can hardly be questioned; here deposition exceeds ablation, the greatest excess is in the warmer months and practically the whole snowfall takes place during high winds. It seems not improbable that the same is true at stations further inland and well above sea-level.

If matter was projected from the sun, in greatest amount at sunspot maxima, and of the same dimensions as volcanic dust, the effect should be an increased temperature

contrast between Antarctic and Equator at times of sunspot maxima. The result would be the same (and possibly peculiarly effective), if the matter projected from the sun and causing auroræ (chiefly in high latitudes) were more absorptive of the sun's than of the earth's radiation.*

So far as direct radiation from the sun is concerned, it is probable that its effect on the climate of the southern hemisphere is also best measured by the contrast between conditions in the Antarctic and the Equator. Assuming the absorption in the sun's and earth's atmosphere to remain unchanged, and the effect of decreasing sunspot activity to result in decreasing radiation received by the earth, we would probably expect a decreased radiation contrast between Antarctic and Equator to result, with less stormy conditions.

The result of an uplift of a low-lying continent when fully covered with ice and snow may lie in increased storminess and in increased precipitation, this increased thickness of snow being compensated in part by a sinking of the land under the increased mass. The increased wind velocity on the continent in these conditions will also result in increased denudation, but the balance will remain in favour of deposition. The uplift of a snow-covered continent which is already high, may, on the other hand, result in conditions in which denudation exceeds deposition, so that the net result may be a loss of snow from the surface.

5. The Origin of Glacial Periods.

The value of the discussion in the preceding pages lies solely in the possibility of correlating periodic climatic changes with changes in other physical and geographical factors, and of indicating what factors are likely to cause decreased temperature, or increased precipitation, in sufficient degree to influence the glacierisation of any portion of the globe. Variations of such short period as those discussed, clearly can have no significant effect, though they may indicate the possible occurrence of variations of much longer period, which may be able to account for the glacial epochs. On the other hand, it is by no means certain that the glacial epochs are of a periodic character and have recurred at equal intervals of time throughout past ages, or will do so in the future. Whether this seems likely to be true, or not, depends largely on one's estimate of the prime causes operating towards increase and decrease of glacierisation, at any stage of a glacial cycle and at any point on the earth's surface.

The probable cause of the glacial epochs has been the subject of speculation for many years, but opinion on the subject is still greatly divided. The rival theories which

* Since the above was written, an interesting article by Fleming ('Nature,' February 2, 1922) has appeared, which discusses the effect of light pressure from the sun on its atmosphere, and the possibility that such particles driven out from the sun may be the cause of the aurora. Whether the earth will be cooled or not by such a projection of matter will depend both upon the density of the material and upon its size. Fleming states that particles of diameter as large as 150×10^{-6} cm., and of density 1, will just be repelled; the diameter of volcanic dust is, on the average, 185×10^{-6} cm. ('Met. Zeit.,' 6, p. 401, 1889). The possibility of such an action may therefore exist.

seem to have the greatest number of adherents at the present time ascribe the cause of the glacial epoch to :—

1. Variation in radiation from the sun.
2. Variation in the eccentricity of the earth (Croll).
3. Vertical uplift of land masses.
4. Volcanic dust in the earth's atmosphere.
5. Combinations of these.

It is not intended to discuss here the relative merits of these rival theories, which has been done with much skill by Humphreys.* We must, however, join issue with him, over his statement that :—

"The practical coincidence of cold ages with mountain-building epochs appears at once and irretrievably to negative the entire group of cosmical ice-age theories—those that assume all great climatic changes to depend on the sun, a condition in space, or anything else wholly outside the earth. Such theories, any solar theory, for instance, must also assume that those external changes, solar changes, say, which caused a marked lowering of terrestrial temperatures, occurred only at about the times of mountain building. That is, they must assume that either : (*a*) the solar changes caused the mountain building, or (*b*) that mountain building caused the solar changes, or, finally (*c*) that both had some unknown but simultaneously acting common cause. But each of these assumptions is wholly untenable." . . "It appears from various considerations that, with a constant or nearly constant output of solar energy, the earth itself possesses the inherent ability to profoundly modify its own climates, whether only local or world-wide. Thus, a mere change in land elevation whether of plateau or of mountain range, a thing that appears often to have happened, must alter both the local and the leeward climates, and, by reducing the general humidity, somewhat lower the average temperature. Besides, a change in land elevation of any considerable extent is pretty certain to be accompanied by a somewhat corresponding variation in continental area, and such modification of shore lines and ocean beds that greater or less changes must follow in the directions, temperatures, and magnitudes of ocean currents, in the location and intensity of permanent 'highs' and permanent 'lows,' in the direction, force and temperature of local winds, in the amount and kind of local precipitation, and in a host of other meteorological phenomena.

"Again, as the laws of radiation indicate must be true, and as observations, at least back to 1750, the date of the earliest reliable records, show, the temperature of the lower atmosphere depends in part upon the amount of dust in the upper air, in the sense that when this amount is great the average temperature at the surface of the earth is below normal, and when the dust is absent this temperature is comparatively high. Hence, as there appears to have been several periods of great volcanic activity in the past with intervening periods of volcanic quiescence,

* 'Physics of the Air,' pp. 627–28.

it is inferred that volcanic dust in the upper atmosphere was at least one important factor in some, if not all, of the great and universal climatic changes that have left their records in abandoned beaches and forsaken moraines.

"How these various causes of climatic changes were related to each other during the geologic past is not yet entirely clear. This the geologist, most interested and most competent to judge, must determine. May it be that extensive upheavals and great volcanic activity often were synchronous? If so, the climatic effects of each obviously were added to those of the other, and hence it may be that the greatest of our past climatic changes were caused by the roughly synchronous variations in continental level and volcanic activity; universal cold periods coming with increase in vulcanism, increase in elevation and the obstruction of interzonal oceanic circulation; universal mild periods when volcanic dust seldom veiled the skies, when the continents had sunk or been eroded to low levels, and when there was great freedom of oceanic circulation from equatorial to polar regions; mild universal climatic oscillations with temporary changes in vulcanism; and mere local climatic changes with variations in such local climatic controls as near-by elevations and neighbouring ocean currents. Finally, as the past is the pledge of the future, it is but reasonable to suppose that the world is yet to know many another climatic change, in an irregular but well-nigh endless series, often local and usually slight, though always important but occasionally, it may be, as in the ages gone—whether towards the auspiciously genial or into the fatefully disastrous—universal, profound and momentous."

In our opinion, the association in short periods of sunspots and earthquakes argues that both have a simultaneously acting common cause within the solar system, and we have no reason to doubt the possibility of a similar cause of longer periodicity, or of non-periodic character. We can readily admit the importance of extensive land elevations in lowering the temperature and the importance of associated changes in the directions, temperatures, and magnitudes of ocean currents, and the possibility (in our opinion, probability) that extensive upheavals and great volcanic activity were often simultaneous. Our suggestion, however, that the cause of such variations need not lie wholly within the earth is surely a reasonable one.

Our view is that all three of the factors mentioned—mountain formation and elevation of land, volcanic activity with the occurrence of volcanic dust in the atmosphere, and sunspot or allied phenomena, affecting the intensity of heat emitted from the sun, *must* operate together and will have a common cause, which may be of a periodic or a non-periodic character, and that this is a possible cause of glacial epochs.

As pointed out earlier in the chapter, the difficulty with which we are faced, when we consider the evidence of climate in past geological ages in the Antarctic, is not to explain the formation of such Ice-ages in the Antarctic, but to explain the prevalence of warmer climates. A similar difficulty results when one considers the glacial epoch of Permo-Carboniferous times, whose influence is traced in South America, South Africa, Australia and India—of which the latter country lies close to the Equator.

The theory of Wegener,* if tenable, seems to solve both these difficulties, to some extent at least, and is a very suggestive and valuable treatise. His contention that the continents float on a more plastic magma of greater density and that they have moved (and are still moving) relative to one another is exceedingly suggestive, and involves, at the same time, a shift of the earth's rotation axis. Wegener gives a diagram showing the assumed position of the continents and the poles in Carboniferous times, and this indicates clearly how the glacial epoch of Permo-Carboniferous times may have simultaneously affected regions which now lie close to the Equator. At the same time, it indicates how the Antarctic Continent may have been immune from the action of ice in the same period. The conceptions of Wegener are revolutionary, but seem worthy of the most critical study. If accepted, they open still another range of phenomena, which makes it even more difficult to decide on the most probable causes of the catastrophic or periodic incidence of Ice-ages in the past and much more difficult to guess the probable course of the future history of the earth. The probability that the Ice-ages are of a non-periodic character, does, however, seem to be much increased, on this view. Catastrophic changes such as the division of one continent from another, would involve changes in the position of the Poles, besides affecting the earth's climate to a very great extent by modifying the oceanic and atmospheric circulations, causing disturbances of the isostatic equilibrium, mountain formation, volcanic activity, etc.

Thus, we are led to the view that, if Wegener's conceptions are correct, all the phenomena we have considered as jointly and simultaneously operating to cause the climatic fluctuations associated with a complete glacial cycle may owe their incidence to a common origin of a catastrophic nature, such as the division of a continent on the earth, and movement of the component parts. If, however, sunspot activity is to be associated with these climatic variations, we must assume that the "gravitational field" on the sun is varied in sufficient degree as a result of these earth movements.

Time alone, and much patient research, can settle these points, but clearly the increase in the number of variables resulting from an acceptance of Wegener's conceptions, must render the facts more easy of explanation—whether the facts are related or independent.

When further information is available regarding the past climatic history of the Antarctic Continent, it may be possible to apply a stringent test to this theory. But our present knowledge is clearly such as to make us welcome a conception which allows the relative position of the South Pole and the Antarctic Continent to have varied in the past.† As pointed out already, the difficulty is, not to explain the incidence of a glacial

* Wegener, 'Die Entstehung der Kontinente und Ozeane,' Braunschweig, 1920.

† The obvious tectonic relationship between East Antarctica and Africa and Australia and between West Antarctica and South America, combined as it is with a distribution of biologic genera and species which seems to demand past land connections between these Continents, is much more easily accounted for if Wegener's theory can be established. The idea of such profound foundering of land bridges between the outlying Continents and the central Antarctic land-mass as must have occurred to account for the present isolation of the latter appears just as revolutionary as Wegener's hypothesis. Indeed, this explanation has lost ground considerably of late years. Yet, some such explanation appears necessary on geological, palæontological, and biological grounds.

climate, but the long periods of warmth enjoyed by this inhospitable land in the dim past.

6. The Influence of Ice-Formations upon Climate.

As pointed out in previous chapters, the thermal constants of an ice surface, and particularly, of a snow surface, differ appreciably from the thermal constants of a water or rock surface. Specific heat, reflectivity and thermal conductivity all differ*, and these differences are such as lead to a greater heating of the air over rock and water in the summer than over a snow surface, and greater heating in the winter over a water surface than over one of rock or snow.

The result, as applied to the Antarctic, may be summarised as a large horizontal temperature gradient in the winter where, as on the Ross Barrier, the snow-covered Barrier meets the open sea. A small horizontal temperature gradient, also with the lower temperature over the snow surface, will be found in the summer months.

At the boundary of a snow-covered and a rock surface, in winter, it is probable that there will be a temperature gradient, in the same sense as that where snow meets water, but of smaller magnitude, while, in the summer, the gradient will be large and in the same sense, *i.e.* the warmer air temperature over the rock.

In lower latitudes, we are probably correct in stating that the same considerations generally apply as in the Antarctic for the summer months. That is—averaging for the year—the air temperature just over the snow will be less than over rock, or over the sea. In either case, there should be a tendency towards a flow of air outwards from the snow surface.

In the case of small snow masses, this tendency will clearly be swamped by the local air circulation. On the other hand, we have seen that ice sheets of continental size are surmounted by a "glacial" anti-cyclone which dominates the air circulation. The question which now arises is this—At what stage does the glacial anticyclone develop?

Before dealing with this point, it will be convenient to trace the growth of an ice sheet to its maximum size as a glacial period in polar regions approaches.

In such a case, as in the Antarctic—supposed previously ice-free—the first permanent covering of snow will probably be formed in the flat sheltered portions of the highlands. Whether the initiation of the conditions leading to the formation of a permanent covering is due to increasing radiation from the sun, to a rise of the land, or to increased precipitation in the area, is not at present of importance. The important point is that there will be a tendency to outward flow of cold air from the snow-covered areas and a slight temperature decrease in the surrounding air. The effect of this will be insufficient to modify the air circulation appreciably, and the result must be a tendency towards increased precipitation of snow and growth in the size of the snow covering.

These conditions will continue until the tendency towards the formation of a local glacial anti-cyclone is sufficient notably to modify the general air circulation in its neighbourhood. It is at this stage that the rate of growth of the ice sheet will become

* *See* Appendix.

slower. When the glacial anticyclone is fully developed, its air circulation will be dominant. If the glacial period is sufficiently severe, growth will continue until such a low latitude is reached that loss by melting sets a limit to the advance of the borders of the Continental-Ice, or until melting in the sea similarly limits its outward extension.

In lower latitudes, the extension of such an ice-sheet will also be limited by the amount of melting at the boundary, and it will be unusual for the sheet to grow to continental dimensions for this reason, and for the reason that only the highest portions of land can ever have such a low temperature that snow can remain throughout the year. In this case, however, growth to the limits attainable, and set by the geographical and climatic conditions, will be quick, whereas this is only true of the first stages of growth in high latitudes.

In both these cases, growth in the appropriate conditions must be quick while the general air circulation is relatively unaffected, that is in the initial stages of the formation of the sheet, before the development of the glacial anti-cyclone. Moreover, conditions which are able to form the first permanent ice-covering on a bare rock surface, will be such as to lead to quick growth of the ice-sheet, once formed. Similarly, conditions favouring decreasing glacierisation will lead to a rapid decrease in the area of the ice-sheet, except in the stable case where the ice-sheet is of dimensions sufficient to maintain a glacial anti-cyclone. In this case, as has been explained already, the area of the ice sheet, the boundary conditions, the contours of the surface and the intensity of the anti-cyclone are all related. In our opinion, a tendency to de-glacierisation in a sheet of Continental-Ice expresses itself first in a decrease in the thickness of the ice, the position of the boundary being maintained by the operation of the glacial anti-cyclone and the drift carried by it. The area of the ice-sheet must, however, also slowly decrease, and the dissolution of the sheet in the final stages must proceed at a very rapid rate.

It seems impossible to arrive at a satisfactory conclusion regarding the size beyond which an ice-sheet may be considered stable in that linear growth and retreat are slow, relative to the linear growth and retreat of smaller ice-sheets exposed to the same climatic conditions. Brooks* has analysed the temperature conditions at 56 stations in Eurasia, between 40° and 60° north latitude, and has found that the effect of land masses on the climate of a place is inversely proportional to the square root of their distance, the remainder of the area being water. Using the same conception,† that the substitution of land ice for ice-free land leads to a fall in temperature proportional to the relative amount of land ice in a circle of 10° angular radius—and, assuming a proportionality factor of 0·2 derived for Alpine regions in the time of the last great glaciation, he arrives at a figure for the critical angular radius of such an ice sheet of 2·5°. Ice-sheets of greater angular radius than this he claims are stable and grow slowly, ice-sheets of less size than this must grow or decrease in size quickly, and are, therefore, unstable. Whatever virtue we may ascribe to Brooks's figures, when applied to an area such as the Antarctic

* 'Quart. Journ. Roy. Met. Soc.,' 1917, p. 159.

† Brooks, 'Quart. Journ. Roy. Met. Soc.,' July, 1921.

Continent, there can be hardly any doubt of the fact that the climatic conditions at any position change notably: (1) when the position becomes snow covered; and (2) when the sheet becomes of sufficient size for the glacial anti-cyclone to dominate the air circulation.

One is tempted to speculate on whether the Antarctic Continent, if suddenly freed from ice, would in present conditions remain free from snow, and whether the Ross Barrier, if it were suddenly annihilated, would re-establish itself. We suggest, though it is little more than an expression of opinion, that, in present conditions, the continent would again become snow-covered, but it is very doubtful if the Ross Barrier would grow again to anything like its present dimensions. We do believe, however, that if the Antarctic Continent of its present dimensions nowhere reached a height greater than 1000 feet, it is very doubtful if the present amount of snowfall would permit the *growth* of a permanent ice-covering, either on land or sea. Such conditions would soon have a notable effect on the sea temperature, and this might, possibly, be sufficient to explain the temperate climate which has been enjoyed by Antarctica for so much of its past. If the continent were, indeed, snow-free in these conditions, we would also expect a very large temperature range between summer and winter, such as is indicated by the Beacon Sandstone formation in many of the exposures studied.

It is certainly unwise to dogmatise on the subject of the influence of the present Antarctic Continental-Ice upon the climate of the southern hemisphere, though there can be little doubt that the temperature difference between North and South Polar regions is considerable, and owes much of its magnitude to the low summer temperatures of the Antarctic summer, caused by the poverty of bare rock on the Antarctic Continent in summer. The view that temperature contrast at the boundary of snow and water, or snow and rock, or at the edge of the Fast-Ice, is the prime cause of the outward flowing wind leads naturally to the view that, the greater the temperature contrast, the greater the storminess and the greater the exchange of air between the continent and lower latitudes of the southern hemisphere. We would then expect greater storminess in the Antarctic to be associated with a higher air temperature in the Antarctic and a lower air temperature in lower latitudes, possibly such places as the southern portions of Australia, New Zealand, etc. We do not know if such a relationship does exist, but undoubtedly a stormy winter in the Antarctic is also a warm one near the coast, due to the fact that the cold air layers near the surface are swept away more frequently, and more frequently replaced by warm air descending from above.

Moreover, as Simpson has shown,* there exists a pressure correlation between the Antarctic and areas in Australasia, South America and the Indian Ocean, which is more pronounced if three months' pressure are compared instead of single months. It is significant that, in the years 1902–3, the interchange of air was apparently chiefly between the Antarctic and the South American region, while, in the stormy years 1911–12, the interchange of air was chiefly between the Antarctic and the Australasian

* 'Meteorology,' vol. 1, pp. 202–205.

region. As stated by Simpson, "it appears that the Antarctic is one of the great centres of action of the world."

That a relationship also exists between the climatic conditions in the Antarctic and those in South America, seems clear from the work of R. C. Mossman, who claims that the temperature and rainfall on the latter continent are largely dominated by the amount of ice in the southern seas. A significant effect may also be due to variations in strength and deflection of oceanic currents, but it is considered such effects will be largely local in character.

It seems quite possible, however, that there will be a definite relationship between the weather of the Antarctic winter, the amount of Pack-Ice formed and driven north and west from the shores of the continent, and the climate in lower latitudes six months or a year later. The variations in Antarctic climate from year to year are very pronounced, and the truth or falsity of such a correlation should be established without much difficulty. If true, the importance of such a correlation would clearly justify, on financial grounds alone, the establishment of a permanent station, or even permanent stations, on the Antarctic Continent.

APPENDIX.

PHYSICAL PROPERTIES OF ICE.

1. Density.

In the process of freezing, water expands about 1/10th. Determinations of the density of ice during the last 50 years have given rather discordant results, due primarily to the presence of dissolved air, but also to the fact, established by Nichols, that the density may vary with the conditions under which the sample of ice was formed, and even with the time since the formation took place.

In Table XX are given some of the density determinations of ice. It will be seen that, in the course of time, ice apparently becomes less dense, and this is due, no doubt, to a rearrangement of the individual crystals through wandering of the molecules after the formation of the ice. It will also be noted that ice formed at low temperatures, as by exposure to a mixture of CO_2 and ether, is less dense than naturally formed ice, such as that of an icicle. This may be due to the inclusion of a greater amount of air.

Table XX.

Density.	Observer.
0·91685	Brunner — Ice formed from boiled water.*
0·91666	Zakrzoski — Ice formed from boiled water.*
0·91615	Nichols — Ice formed from boiled water.*
0·91772	Nichols — Ice formed from boiled water.*
0·91600	Vincent — Ice formed from boiled water.*
0·91720	Leduc — Ice formed from boiled water.*
0·91806	Nichols — Natural ice.*
0·91644	Nichols — Natural ice.*
0·91661	Barnes and Cooke — Natural ice.*
0·91619	Nichols. Ice mantles (CO_2 and ether).
0·91590	Nichols. Ice mantles.
0·91636	Nichols. Ice mantles.
0·91816	Nichols. Natural ice (icicles).
0·91801	Nichols. Natural ice.
0·91804	Nichols. Pond ice freshly cut.
0·91644	Nichols. Pond ice one year old.

* Barnes, "The Physical Constants of Ice," 'Trans. Roy. Soc. Can.,' vol. 3, section 3, 1910.

2. Coefficient of Thermal Expansion.

The coefficient of thermal expansion of ice is a constant that has received very little attention. In Table XXI, taken from Barnes,* are given the determinations which have so far been made, and it will be seen that these show no remarkable degree of uniformity.

So far back as 1886, Andrews measured the linear coefficient of expansion per degree Fahrenheit, and found it to vary with the temperature in the following way :—

From	−30° F. to −21° F.	.. ..	0·000019744
	−21° + 0°	.. ..	20484
	+ 0° −16°	.. ..	28042
	+16° +32°	.. ..	40876

It will be seen that the coefficient of expansion per degree Fahrenheit from 16° to 32° F. is twice that observed between −30° and −21° ; that is, the coefficient increases with increasing temperature.

Though no data are available, it is quite certain that the coefficient of linear expansion will be different in single ice crystals for different directions relative to the axes.

Table XXI.—Coefficient of Linear Expansion per degree Centigrade.

Pettersson ...	0·000053 (—12° C. to —2)
Nichols... ...	0·000054 (—10° C.)
Vincent ...	0·0000507 (—10° to 0°)
Dewar	0·000027 (—189° to 0°)

3. Thermal Conductivity.

A knowledge of the thermal conductivity of ice is of considerable importance, on account of the protection against temperature change afforded to the ground by a layer of ice or snow, and the consequent effect of such a deposit upon the earth and air temperatures.

Observations to determine the conductivity along different axes have not given consistent results, but it seems clear, from the work of Forbes and Straneo, that no very large difference exists between the conductivity measured parallel to and perpendicular to the optic axis. The values for the conductivity are given in Table XXII.

Table XXII.—Thermal Conductivity of Ice.

Observer.	Conductivity along principal axis.	At right angles to principal axis.
Forbes... ...	0·00224	0·00214
Neumann ...	0·00573 (direction not given) ...	—
Straneo ...	0·0050	0·00514
Straneo ...	0·00517	—

* Barnes, 'Ice Formation,' London, Chapman & Hall, 1906.

† Barnes, 'The Physical Constants of Ice,' *loc. cit.*

Observations on the thermal conductivity of snow have shown that the value depends, not only on the density of the snow, but also on the form and size of the snow crystals. Abels, by the use of thermometers buried to different depths in snow, obtained the relation—

$K = 0 \cdot 00677 \, d^2$, the extreme values being :—

For light snow	0·000017
For dense snow	0·00548

Jansson has derived the formula $K = 0 \cdot 00005 + 0 \cdot 0019 \, d + 0 \cdot 006 \, d^2$, where d is the density of the snow.

Okada has also made observations on the value of K, using the same method, and has obtained the following results :—

For depths 10–20 cms., K = 0·00028 C.G.S. (density of snow about 0·18).
„ 20–30 „ 0·00045 „ „ „ „ 0·24).

These agree quite well with the formula given by Abels.

The conductivity of fresh fallen snow is therefore very small in comparison with that of ice, and this enables one to realise how very much more efficient as a heat retainer is a cave fashioned out of snow than a similar one built of ice.

[The thermal conductivity of different rocks varies considerably, but the average is about 0·004.*]

As an illustration of the low heat conductivity of snow and ice, the temperature observed in the ice caves (excavated for magnetic and pendulum observations) are plotted in Figs. 175 and 176, which also show the air temperature curve during the same period.

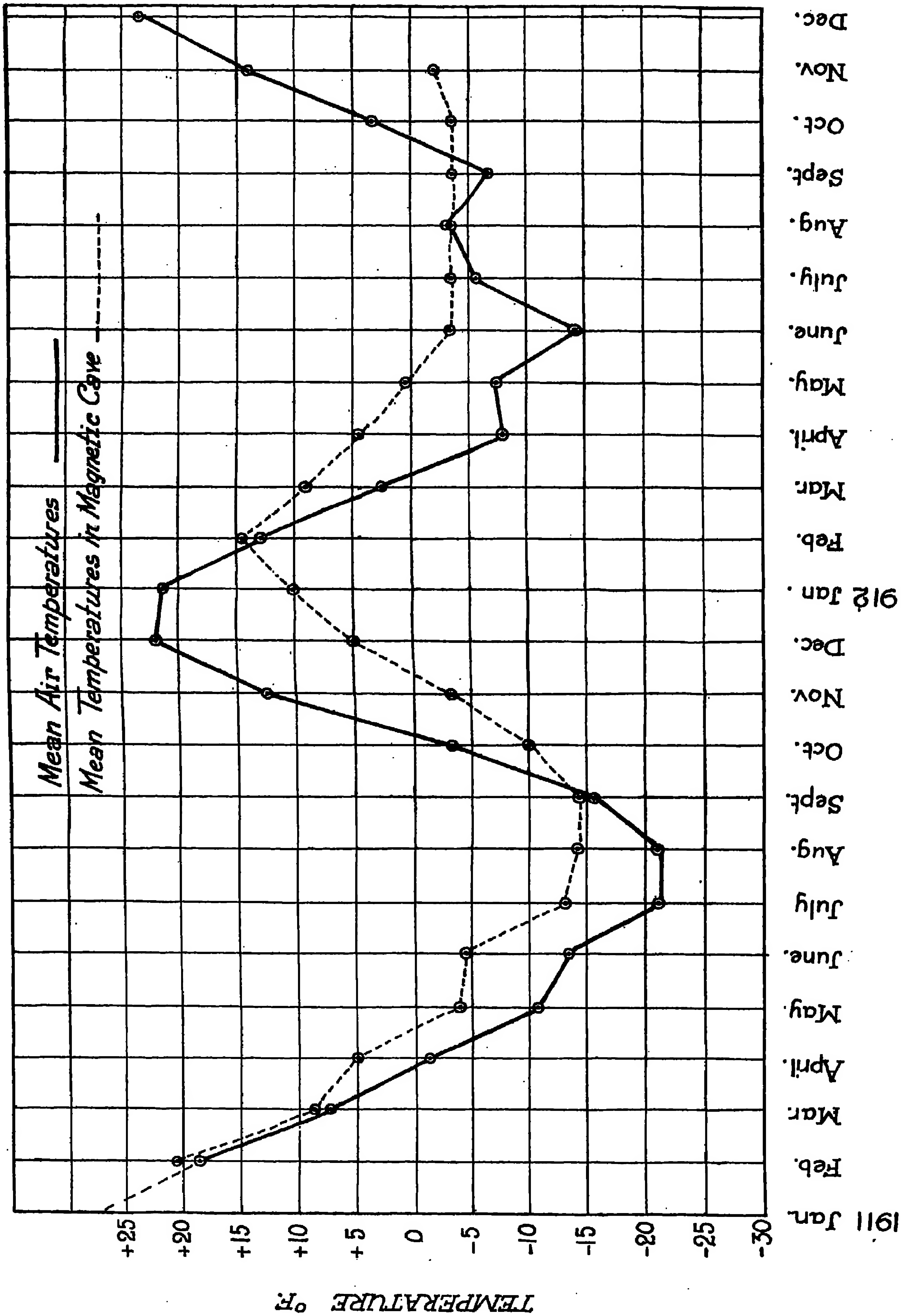
4. Diathermancy.

Little is known of the diathermancy of ice, *i.e.* its power of transmitting heat and light waves. According to Melloni, only 6 per cent. of the energy from a Locatelli lamp is transmitted through a plate of ice 2·6 mm. thick; while, if a source consisting of blackened copper heated to nearly 400 degrees is used, no effect whatever can be detected through the same screen. It would seem at first sight, therefore, as if the effect of a covering of ice on a sheet of water must be to stop all radiation of the long heat waves, so that practically the only cooling the water can experience must take place by conduction through the ice-covering.

That this is not the case, however, seems to be proved by experiments conducted by Barnes. On page 15 of his 'Ice Formation,' he says :—" I have recently made some experiments on the absorption of terrestrial radiation, and, although they are not yet by any means complete, they point very strongly to the fact that water, and especially clear ice, is transparent to a large proportion of the radiation from the earth into space."

The experiments were conducted with platinum resistance coils wound on mica frames and blackened, and each enclosed in a box blackened on the inside. When one

* Joly, 'Radioactivity and Geology,' p. 74, Constable, London, 1909.



Mean Air Temperatures
Mean Temperatures in Magnetic Cave
TEMPERATURE °F
+25
+20
+15
+10
+5
0
-5
-10
-15
-20
-25
-30
1911 Jan.
Feb.
Mar.
April.
May.
June.
July
Aug.
Sept.
Oct.
Nov.
Dec.
1912 Jan.
Feb.
Mar.
April.
May.
June.
July.
Aug.
Sept.
Oct.
Nov.
Dec.

Fig. 175.

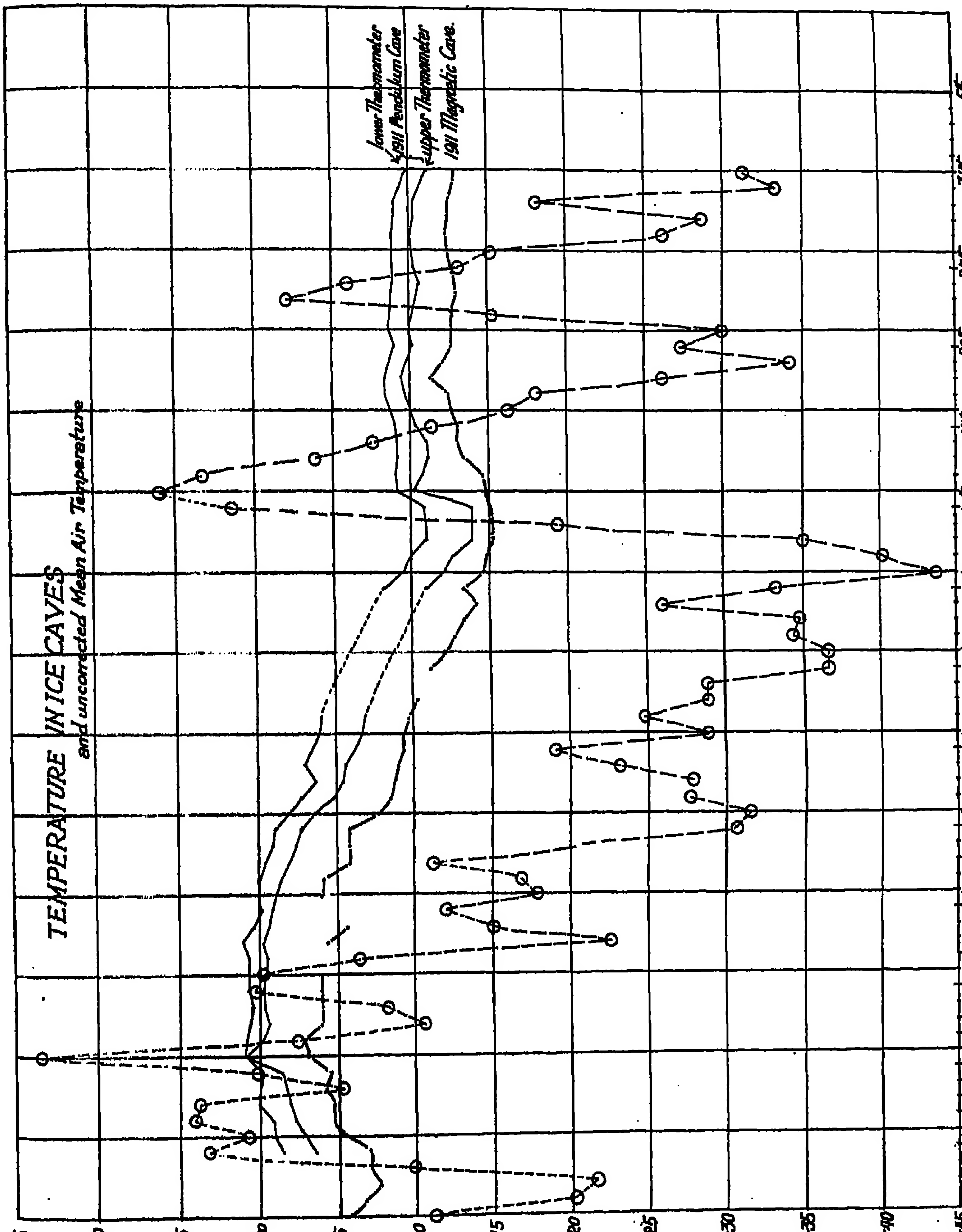

TEMPERATURE IN ICE CAVES
and uncorrected Mean Air Temperature
Lower Thermometer 1911 Pendulum Cave
Upper Thermometer 1911 Magnetic Cave.
Degrees Fahrt
+15
+10
+5
Zero
-5
-10
-15
-20
-25
-30
-35
-40
-45
27th May
1st June, 1911
5th
10th
15th
20th
25th
30th July
5th
10th
15th
20th
25th
31st Aug
5th

Fig. 176.

coil was left uncovered to the sky at night, during the Canadian winter, it was found to have become cooler than the covered coil by 5° to 9° F. A block of clear ice 2 inches thick, placed over the uncovered thermometer, cut off only a small proportion of the radiation. This is a result of considerable importance, for it is with temperature conditions similar to those under which the above experiment was carried out that this memoir chiefly deals. As a rule, however, in the Antarctic, as in other parts of the world where ice occurs in quantity, we have not to deal with large expanses of clear ice, but of ice rendered opaque by the presence of impurities. Clear ice does occur, however, as in the case of many of the numerous moraine or rock basin lakes.

5. Latent Heats of Fusion and Vaporisation.

The amount of heat in calories required to change 1 gram of water at 0° C. into ice at the same temperature, is known as the Latent Heat of Fusion. Determinations of this constant for ice give a value about 80.

Thus, the amount of heat that must be abstracted from a mass of water at freezing-point, in order to convert it into ice at the same temperature, is equal to that which will raise the same mass of water through 80° C.

The latent heat of sublimation of ice is given by Barnes and Vipond as 600 calories at 0° C., a higher figure being obtained when the evaporation takes place more slowly.

6. Specific Heat.

Of chief interest in this connection is the variation of specific heat with temperature, since this is of importance in the winter months as a factor affecting the formation of cold air layers on the snow surface of such Ice-Formations as the Ross Barrier. The specific heat per unit volume of loosely compacted snow is low even at freezing-point, but is even lower at the temperatures observed in such conditions during calm weather. Table XXIII gives some of the data relating to the variation of the specific heat of ice with temperature.

Table XXIII.

Temperature Range.			Specific Heat.	
° C.		° C.		
− 20	to	0	0·504	Person.
− 78		− 18	0·463	Dewar.
−188		− 78	0·285	Dewar.
−252·5		−188	0·146	Dewar.

The specific heats of most rocks at ordinary temperatures are not far from 0·2.

7. Vapour Pressure.

Data relating to the vapour pressure of ice are shown in Table XXIV, and, for comparison, values of the vapour pressure of water are also given. It will be noted that the vapour pressure of ice is always less than the vapour pressure of water at the same temperature. Fig. 177 illustrates the variations with temperature of the vapour pressure of water.

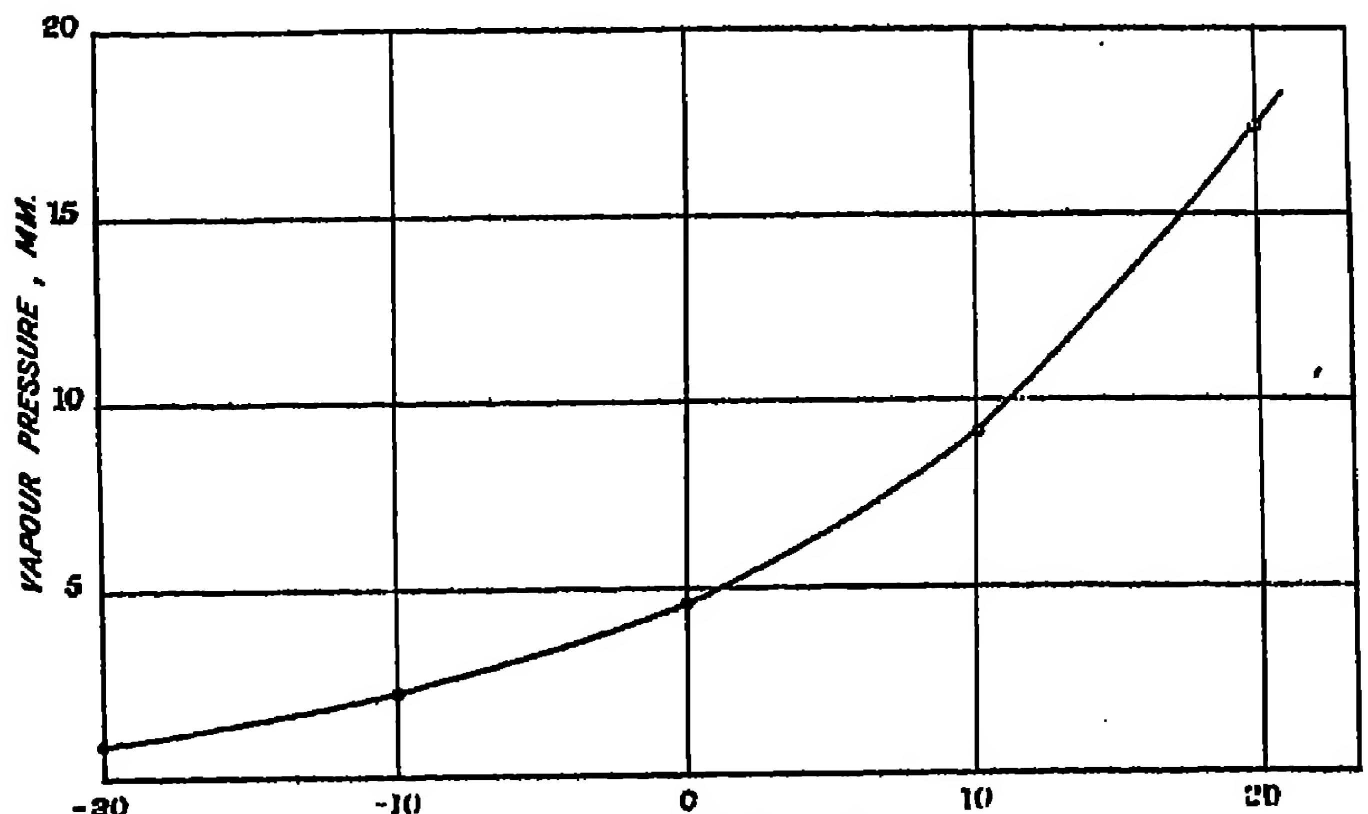


Fig. 177.

At low temperatures, such as − 50° C., the vapour pressure of ice is very slight. In fact, if all the moisture in a column of air, 10 km. in height, if saturated and at this temperature, were deposited on the surface beneath, it would be equivalent to a rainfall of about ⅓ mm. only. At 20° C., the equivalent deposition would be about 17 cm., or some 560 times as much.

Not only therefore should we expect snowfall to be much less at low temperatures than at high, but we should also expect the evaporation from ice surfaces to be much less at (say) −30° C. than at the freezing-point. In this case, however, it must be remembered that the velocity of the wind to which the ice is exposed is a very potent factor in promoting ablation.

Table XXIV.*

Water.		Ice.	
Temperature.	Pressure.	Temperature.	Pressure.
° C.	(mms. Hg.).	° C.	(mms. Hg.).
20	17·539	0	4·579
10	9·210	—10	1·947
0	4·579	—20	0·770
—10	2·144	—30	0·280
—16	1·315	—40	0·094
		—50	0·029

* 'Physikalisch-Chemische Tabellen,' Landolt Bornstein, 4th ed.

8. Melting-Point and Pressure.

Of all the properties of ice, one of the most important in its effects is the lowering of the melting-point under pressure.

This property is general for all substances which expand on freezing, and the theoretical amount of lowering of temperature can be calculated from the known constants of ice. Dewar* gives the observed value 0·0072° C. for each atmosphere pressure up to 700 atmospheres.

One result of this property of ice is best illustrated by example. If we have a glacier with a uniform temperature of (say) −0·07° C. throughout its mass, and we consider the weight of 36 feet of ice as equivalent to one atmosphere, then at depths below 360 feet the ice can no longer exist in the solid phase, but will flow out in the form of water. The maximum thickness a glacier at this temperature can attain is therefore 360 feet.

Tammann has lately worked out more fully the relation between pressure and melting-point. He finds that several forms of ice may be recognised, depending on the conditions of temperature and pressure. Ice kept at a temperature of −20° C. will, under increasing pressure, first become liquid for a pressure of about 2050 Kg/Cm^2. On further increasing the pressure to 2640 Kg/Cm^2, the mass will again become solid. These phases can all be seen for any temperature from 0° C. to −22° C., but, below the latter temperature, no amount of pressure can make the ice assume the liquid form.

9. Elasticity.

The determination of the elasticity of ice by the methods applicable to other solid bodies is an undertaking of considerable difficulty, owing to the large permanent changes undergone by ice under strain. Hess† gives for the modulus of elasticity (E) the value 27600 Kg/Cm^2, as the mean of a number of experiments on glacier ice and on bars cut at different inclinations to the optic axis. Reusch, using sounding plates of ice, found the value to be $E = 23632$ Kg/Cm^2.

10. Viscosity and Movement of Ice under Pressure.

The viscosity of ice appears to have been first determined by McConnell from the bending of bars of ice under given loads. His values (calculated by Deeley) lie between 3×10^{10} and $1 \cdot 34 \times 10^{12}$ C.G.S. units, and indicate that the viscosity becomes less as the temperature of the ice rises. Weinberg, by the use of a torsional method, found the relation—viscosity $= (1 \cdot 244 - 0 \cdot 502T + 0 \cdot 0355T)^2 \; 10^{13}$ gm/cm. sec.

Deeley, by rough calculation from the size and velocity of different Swiss glaciers, gives the values shown in Table XXV.

* Dewar, 'Proc. Roy. Soc.,' vol. 30, 1880.

† Hess, 'Die Gletscher.'

TABLE XXV.

Viscosity.	Observer.	Calculated by
6·0×10¹²	Dr. Main	Deeley.
84·5 ,,	McConnell and Kidd ...	Deeley.
8·0 ,,	B. Weinberg	Weinberg.
17·4 ,,	Blumcke and Hess ...	Weinberg.
78·9 ,,	Tyndall and others ...	Deeley.
17·5 ,,	Blumcke and Hess ...	Weinberg.
147·7 ,,	Blumcke and Hess ...	Deeley.
125·0 ,,	Blumcke and Hess ...	Deeley.

Hess has also made observations on the viscosity of mixtures of ice and sand, and concludes that it is greater than that of pure ice. It is, however, not altogether certain that, under natural conditions in a glacier, the increased viscosity of the ice-cement may not be more than made up by the decrease in viscosity due to a higher temperature, brought about by the heating effect of absorbed radiation.

A very interesting outcome of the experiments carried out by Hess on the bending of ice-bars in directions at right angles to the optic axis, is delineated in Fig. 178. Here

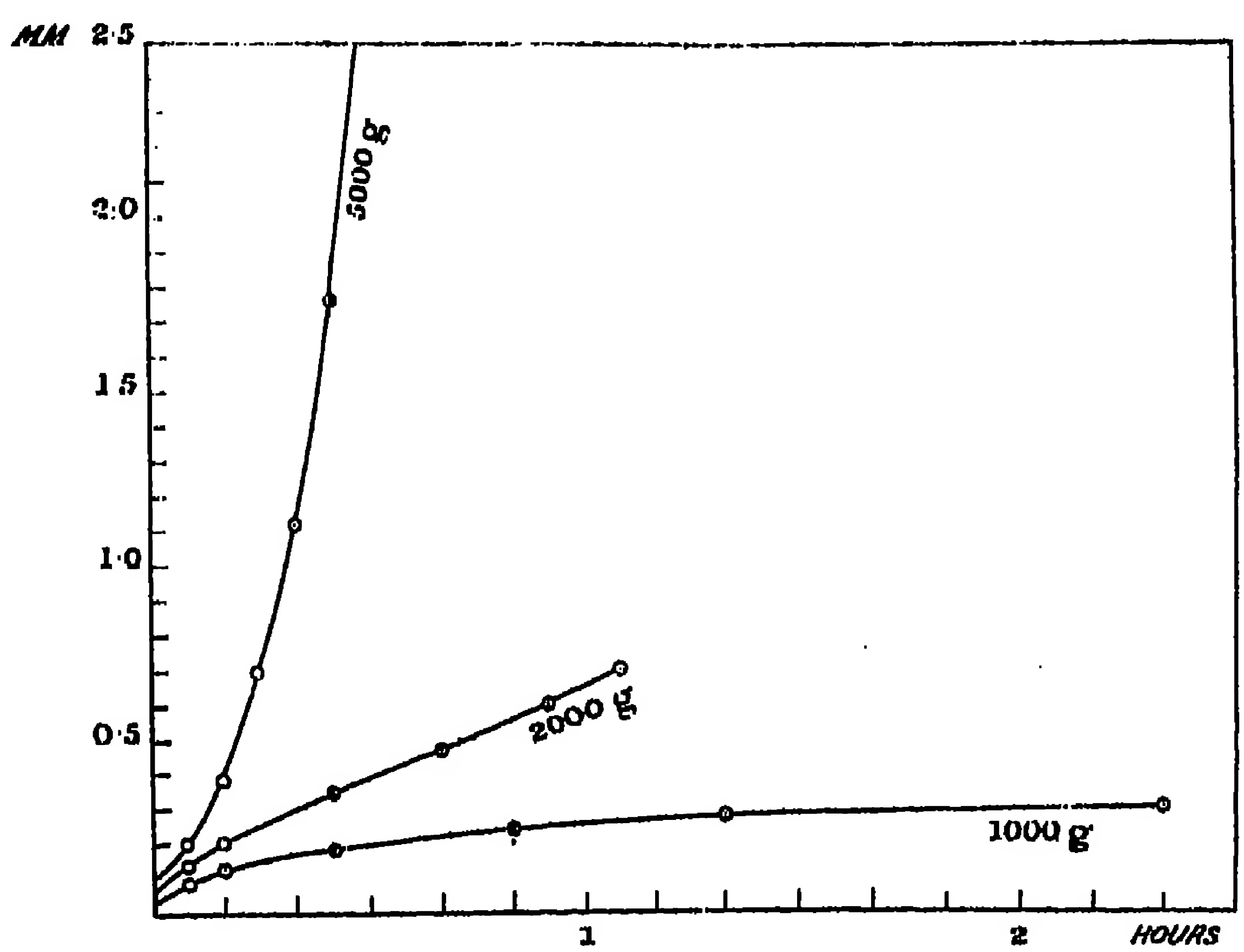


Fig. 178.

the ordinates represent the distance the bar has been bent in millimetres and the abscissæ the time in minutes since the load was applied. Hess expresses his results in the following form :—

For small loads, rate of deformation $= ds/dt = a/t$.

,, moderate ,, ,, ,, b.

,, large ,, ,, ,, ct;

where t = time elapsed and a, b and c are constants.

Though these equations are by no means exact, still the tendency in glacier ice seems to be in the direction shown, viz., the motion for heavy loads increases with time, for moderate loads is constant, and for small loads decreases with time.*

Perhaps some of the most interesting experiments on the viscosity of ice have been carried out by Hess and by Tammann.† Ice frozen in a steel tube was forced through a small orifice by pressure on a piston above, the whole apparatus being usually surrounded with snow. The results obtained by these investigators are set down in Table XXVI. It will be seen that the pressure necessary to keep up a constant flow is dependent both on the area of the hole through which the ice is forced out, and upon the temperature of the ice.

TABLE XXVI.

Area of Orifice.	Pressure (Kg/cm²).	Change of Section.
—	500	14 : 1
78·5	345	9 : 1
113·0	230	6·3 : 1
223·0	100	3·1 : 1
—	30	1·67 : 1
113	230	Temp. = 0° C.
113	250	—3° to —5° C.
113	270	—10° C.
	Temperature 0° C.	

In Fig. 179 are plotted some further results obtained by Hess, showing the way the velocity of flow through such orifices depends upon the load (temperature being constant).

Roughly speaking, the motion is directly proportional to the pressure applied and inversely proportional to the difference between the pressure applied and that which must be applied to make the ice melt, or, in other words, to give it a very large velocity of outflow. In all these experiments by Hess, it is found that the velocity increased with lapse of time.

Barnes, on page 66 of his 'Ice-Formation,' reproduces a very interesting curve obtained by Andrews, showing the penetrability of ice by a loaded piston at different temperatures. Roughly speaking, the penetration under the weight applied is inversely proportional to the difference between the melting temperature at atmospheric pressure and the actual temperature during the experiment. It is not, however, clear from Andrews' paper in what respect time has been considered as a factor.

Hess further investigated the change in grain size of ice squeezed in such an apparatus. This he did by counting the number of crystals at different places within the ice mass. In one experiment he found that the mean size of the crystals close to

* Compare Nutting, 'Journ. Franklin Inst.,' May, 1921. Displacement $s = at^nF^m$, where t = time, F = applied force, and a, n and m are constants independent of s, t and F.

† Hess, 'Die Gletscher,' p. 28.

the periphery was 0·029 mm. and, in the centre, 0·020 mm. After the piece of ice had remained for several hours at the freezing temperature, it was squeezed through an opening, so as to suffer a change of diameter of nearly one-half. On re-counting the number of crystals, Hess found that the diameter of the crystals along the periphery was now 0·053 mm., and those in the centre 0·046 mm. Under these conditions, the crystals had therefore grown to almost double their size in the short space of a few hours.

That the growth of some of the crystals inside a mass of ice does occur, even without the apparent assistance of pressure, is now recognised. The phenomenon may be seen

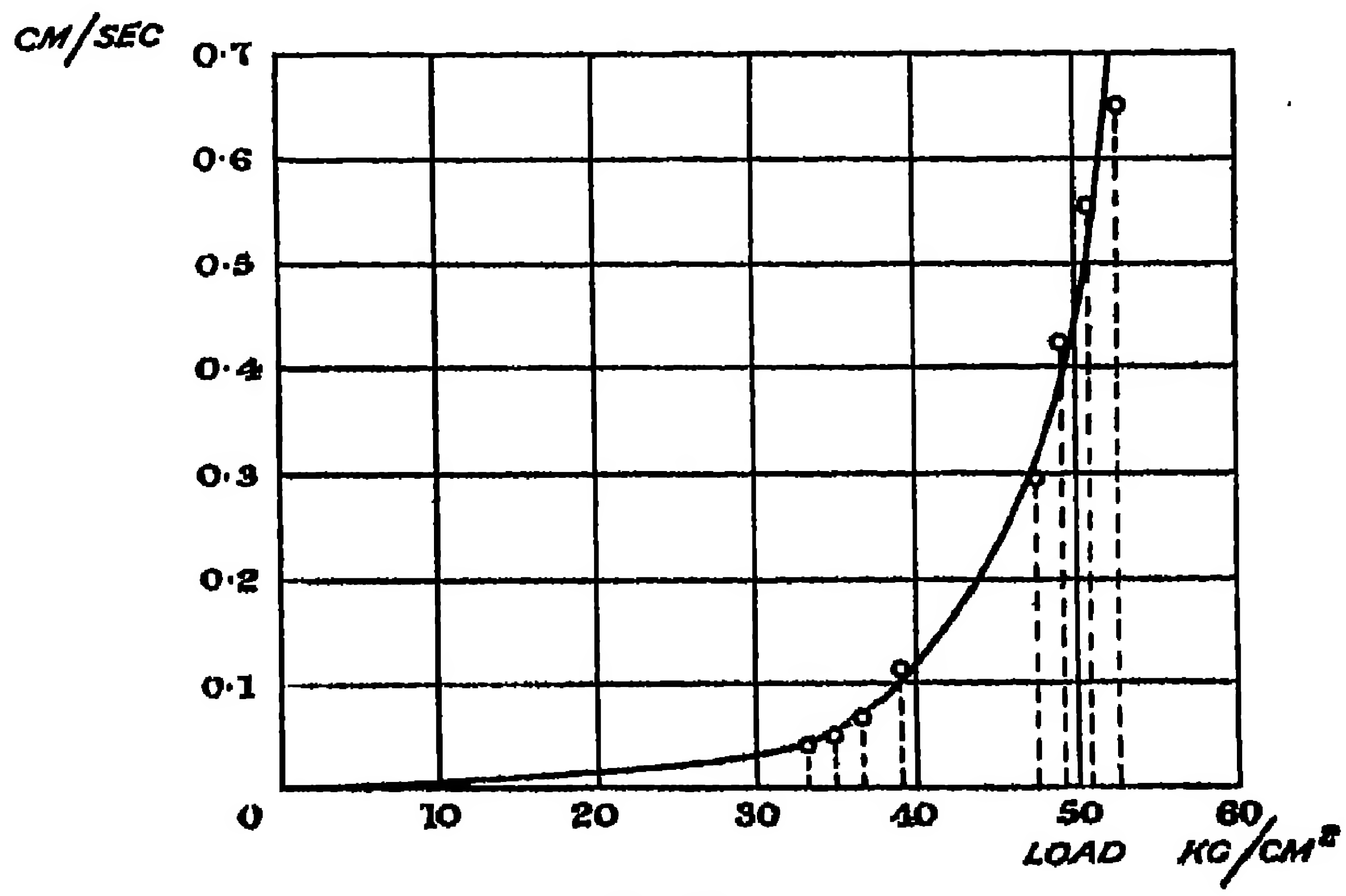


Fig. 179.

daily on the névé fields of any glacier in temperate climates, the larger crystals growing from the fallen snow at the expense of the smaller, until some have reached a diameter of an inch or more.

The rate of growth of crystals is of course largely conditioned by the temperature, but it is clear that, even on the Ross Barrier, where the snow surface never rises to the freezing-point, the same process of growth is taking place, though at a much slower pace than in more genial climates.

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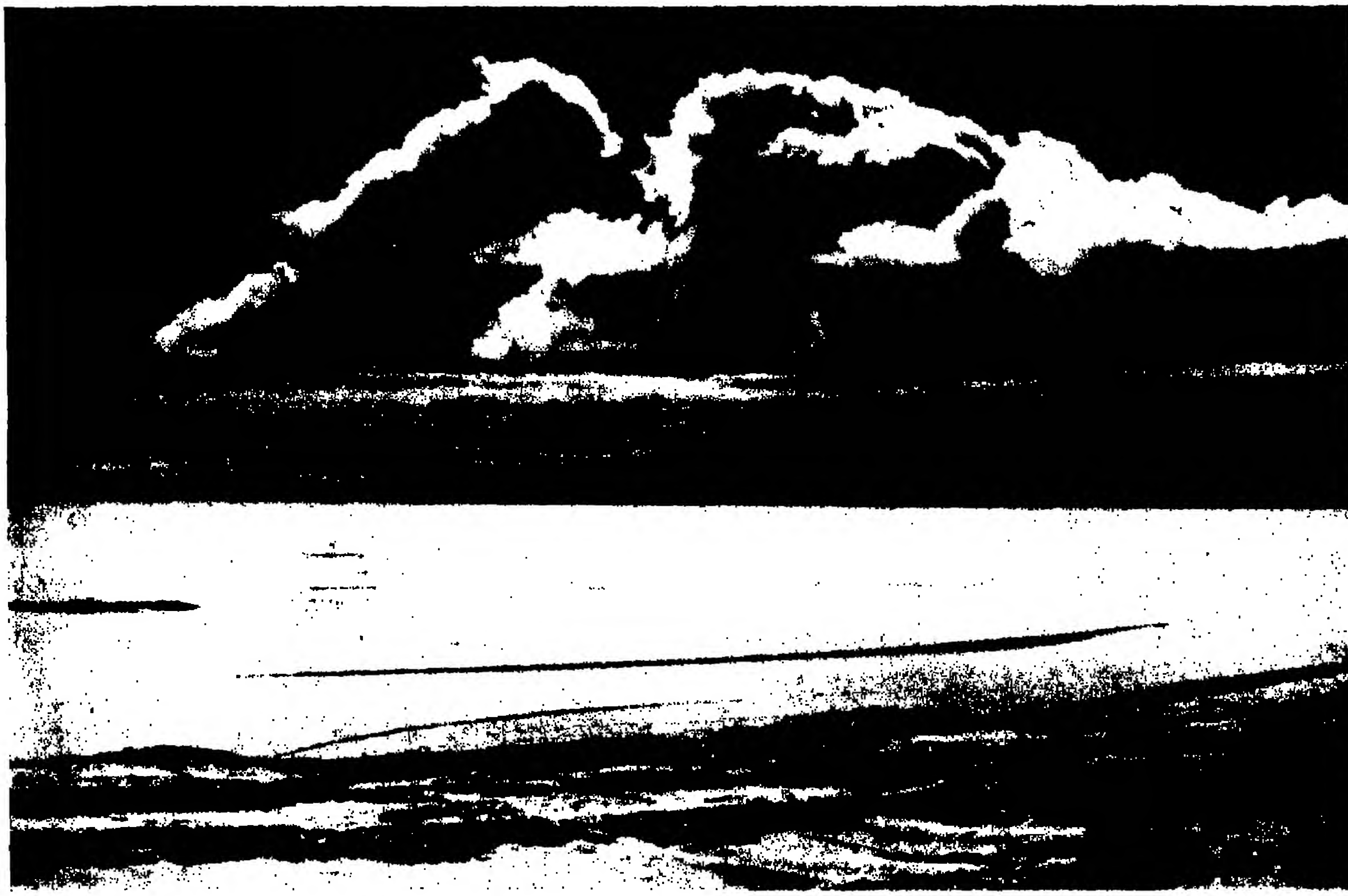

Plate I.—Cumulus Cloud over Cape Barne, Ross Island.

Page 7. *Photo by Ponting.*

Plate II.—Cumulus Cloud over Mount Cloudmaker, Beardmore Glacier Region.

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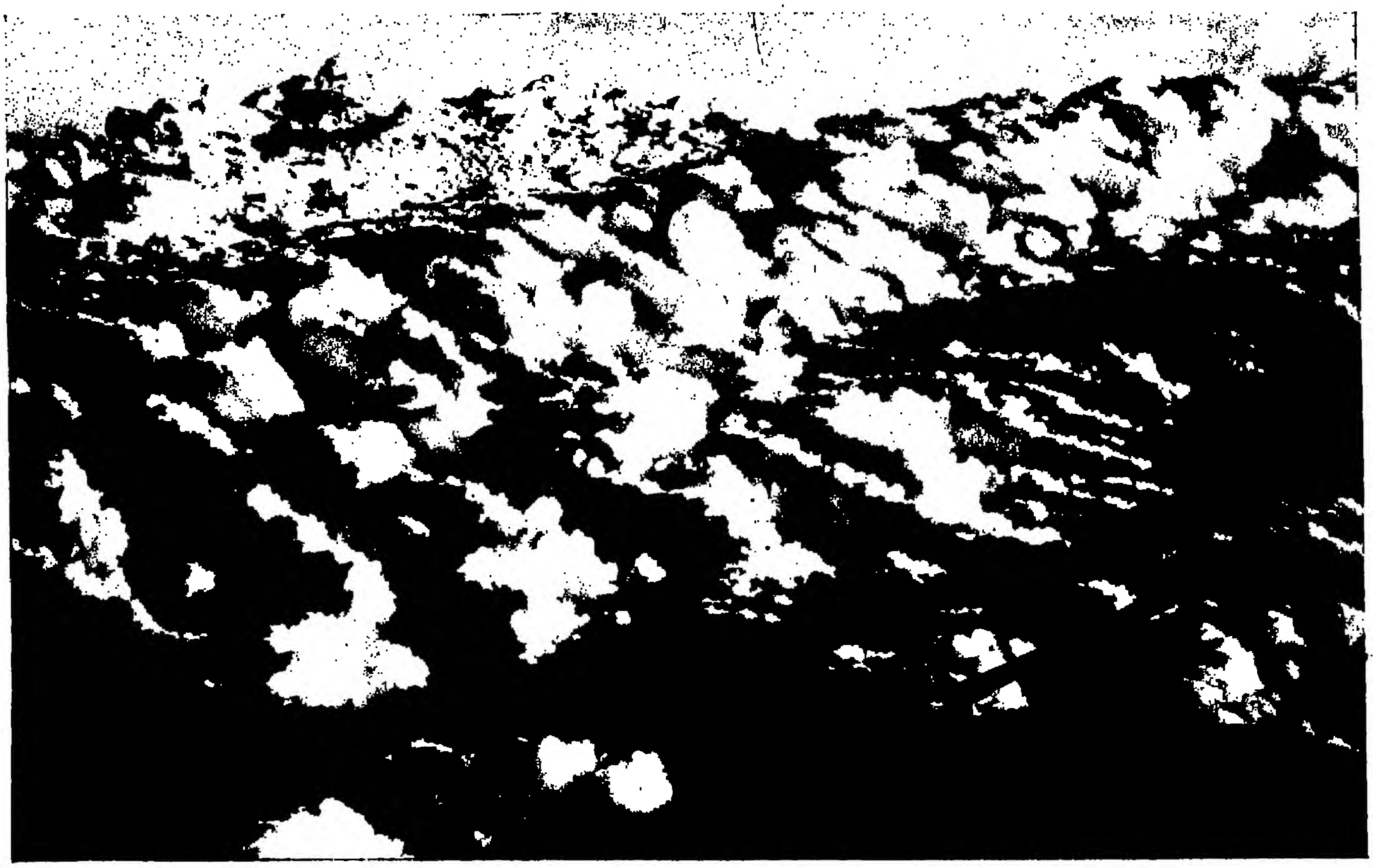

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Photo by Ponting.

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Photo by Scott.

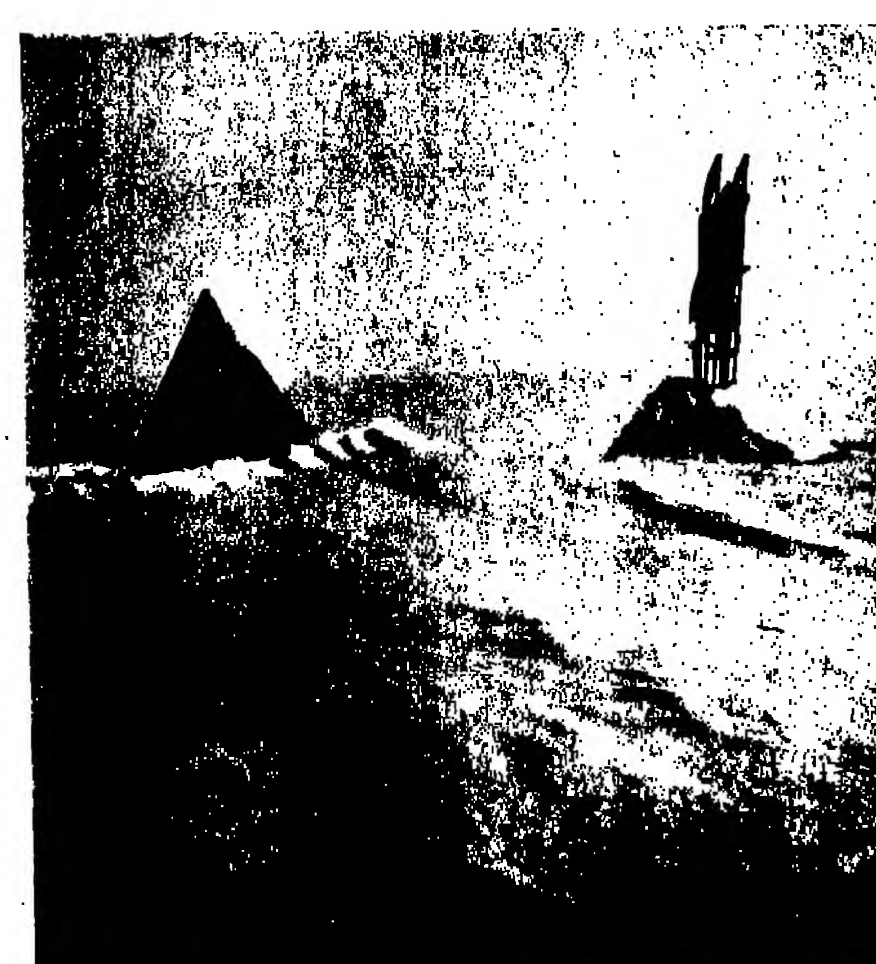

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Photo by Wrig

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Page 20. *Photo by Priestley.*

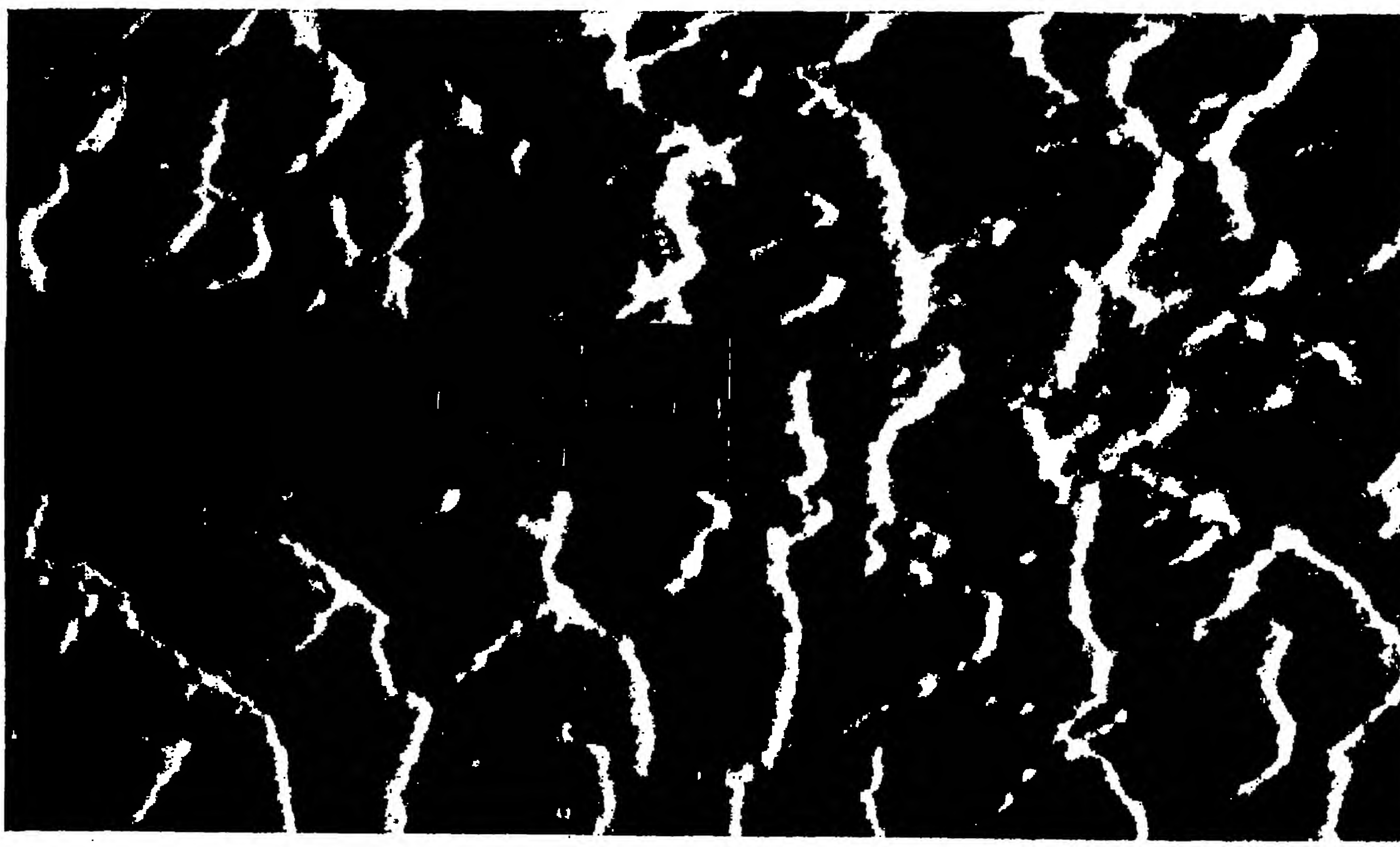

Plate IX.—Ripple-marked Surface after light wind. × $\frac{2}{3}$

Page 33. *Photo by Ponting.*

Plate X.—Rippled Surface of wet sea ice (after blizzard).

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Photo by Ponting.

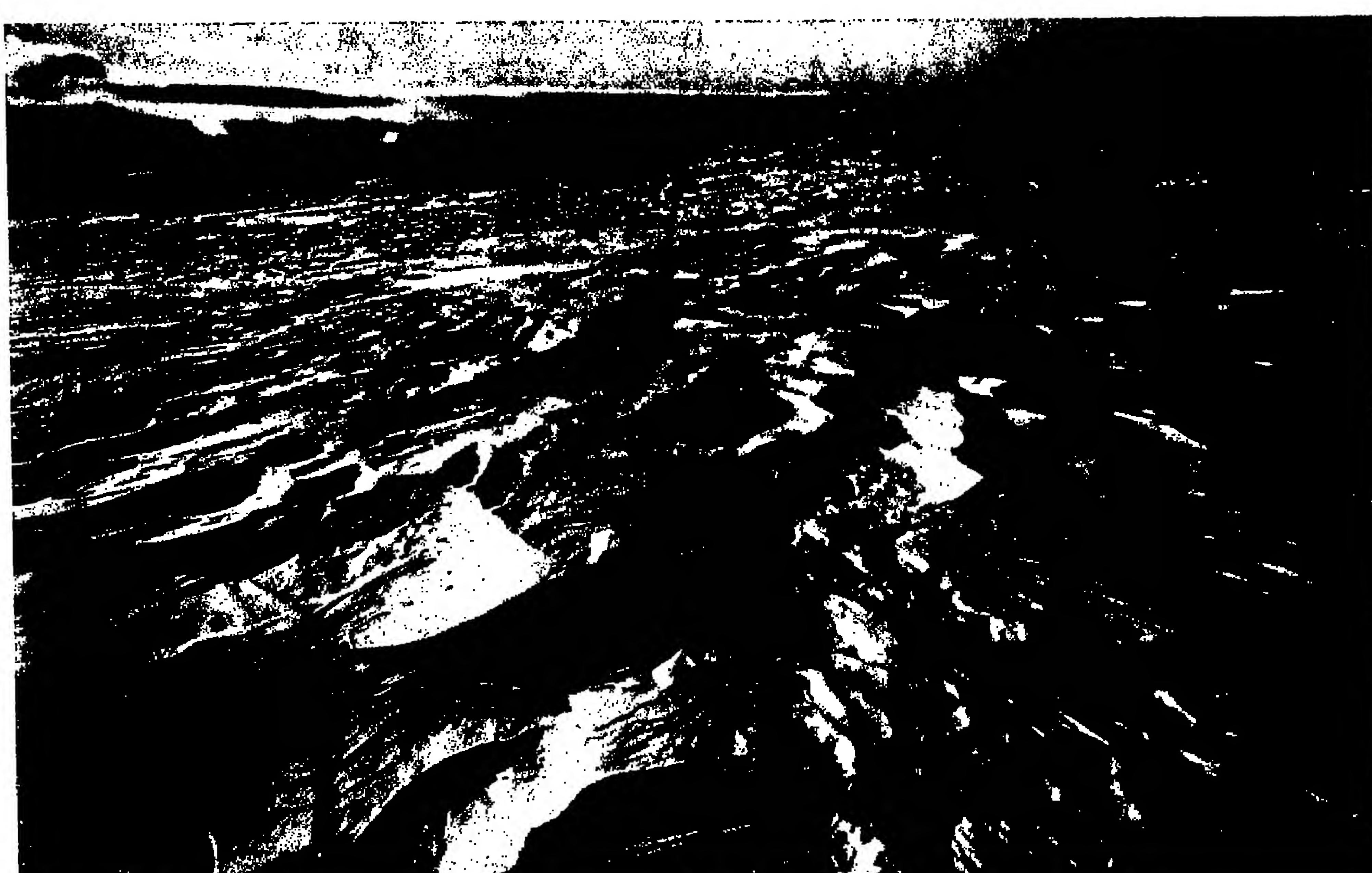

Plate XV.—Marbled Sastrugi, looking down wind, Barne Glacier.

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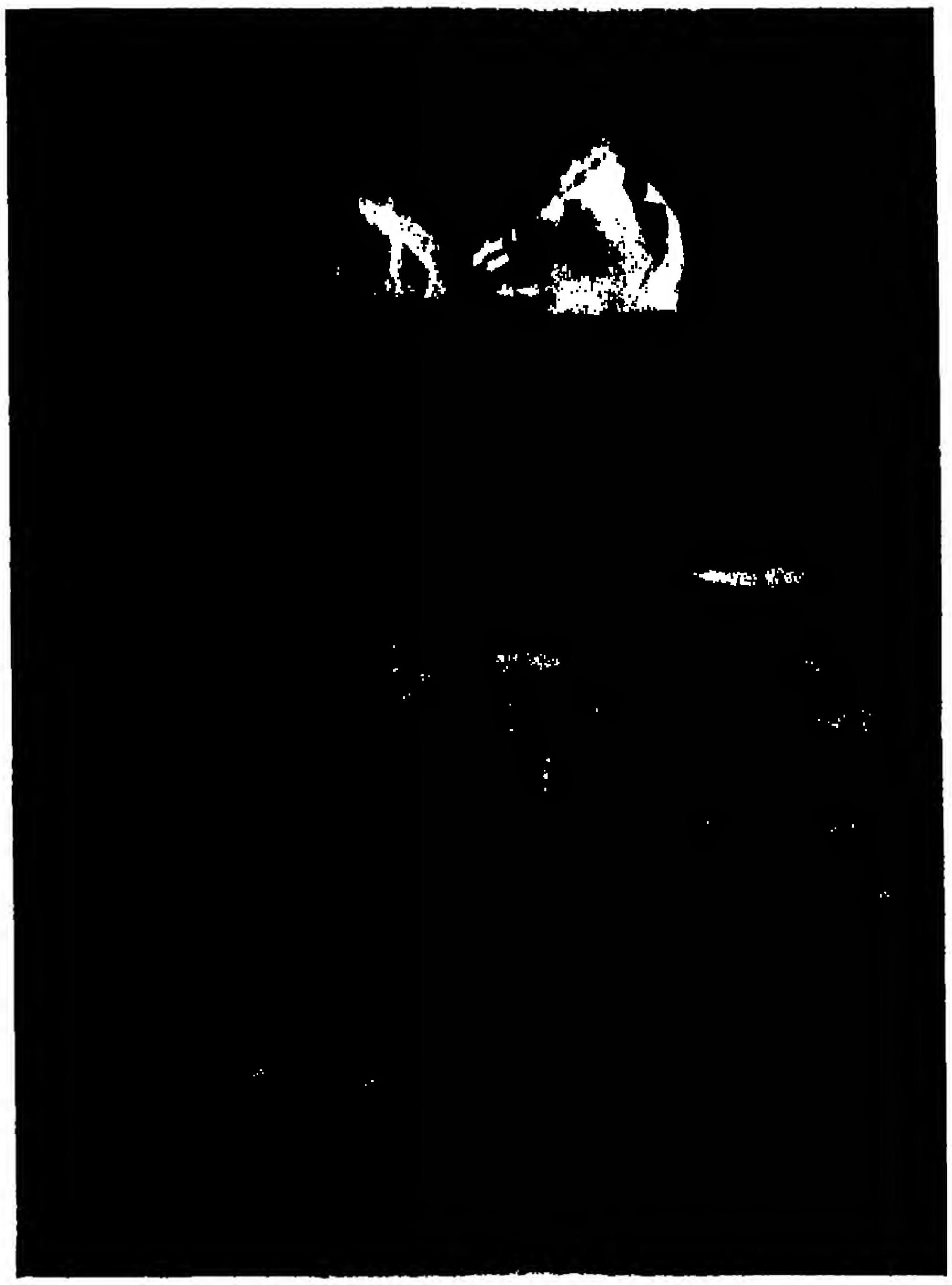
Photo by Ponting.



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Page 36. *Photo by Wright.*

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Page 37. *Photo by Scott.*

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Page 41. *Photo by Wright.*

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Page 41. *Photo by Levick.*

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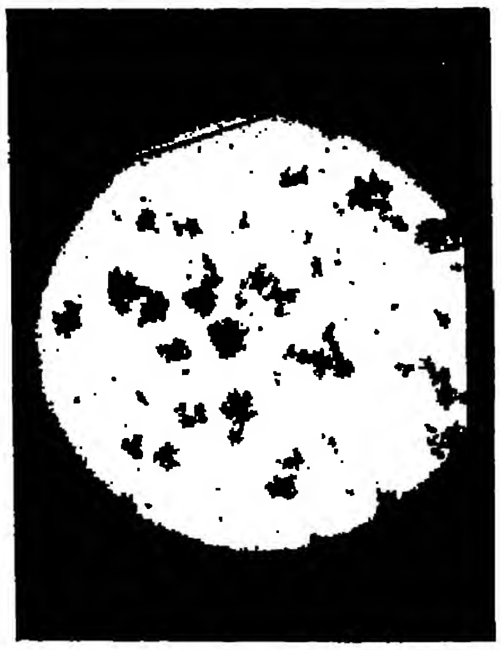

Plate XXVI.—"Fluff-ball" Snow. ($\times 2\frac{1}{2}$)

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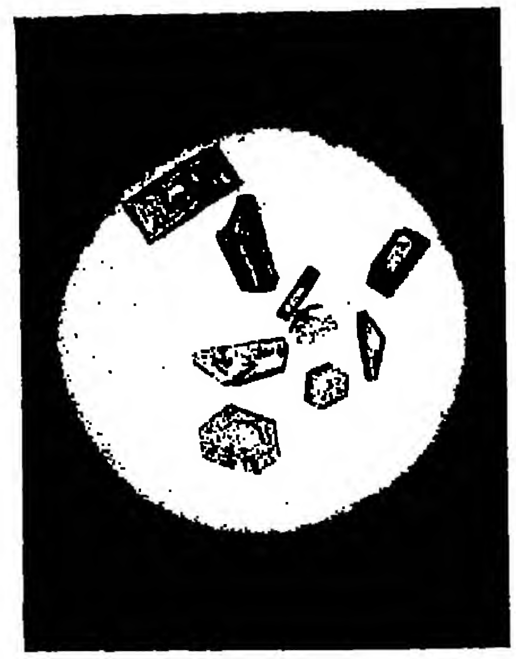

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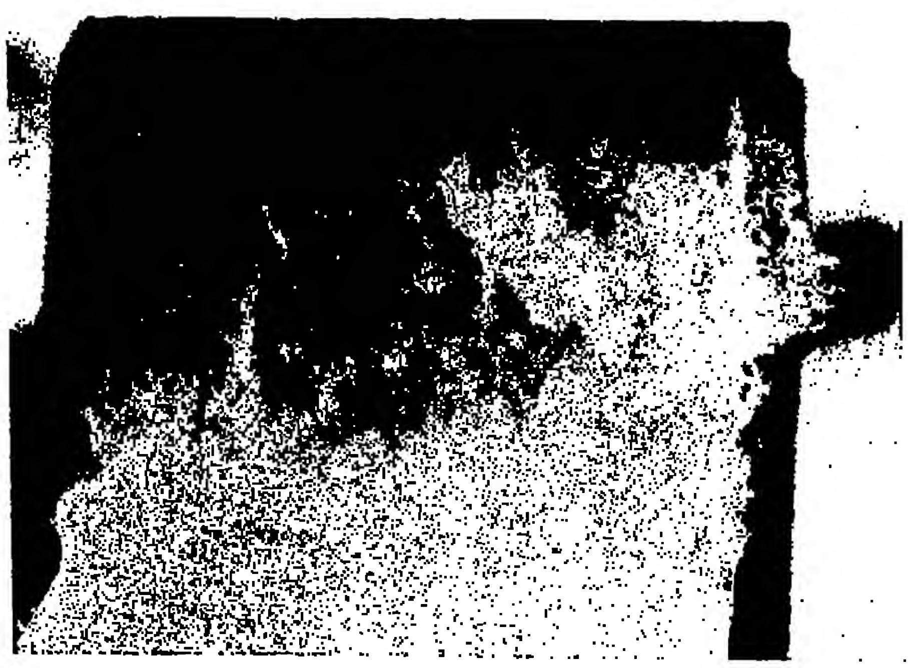

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Photos by Wright, except No. XXIX by Levick.

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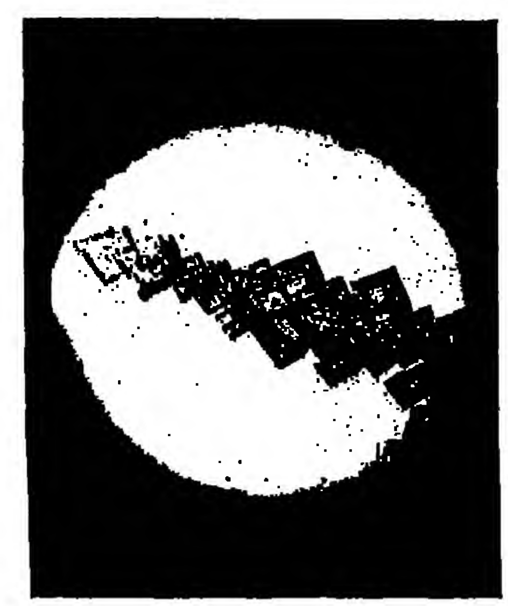

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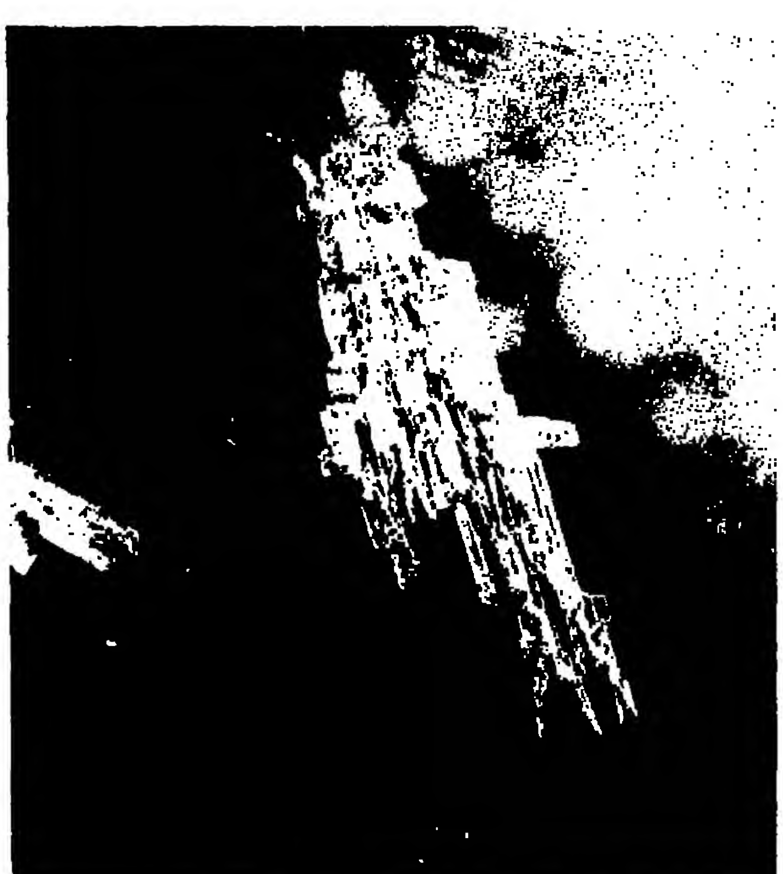

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XXXIX.—Frost Crystals. ($\times 5$)
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Plate XL.—Frost Crystals. ($\times 5$)
Page 71. *Photos by Wright.*

Plate XLI. (× 10)

Plate XLII.

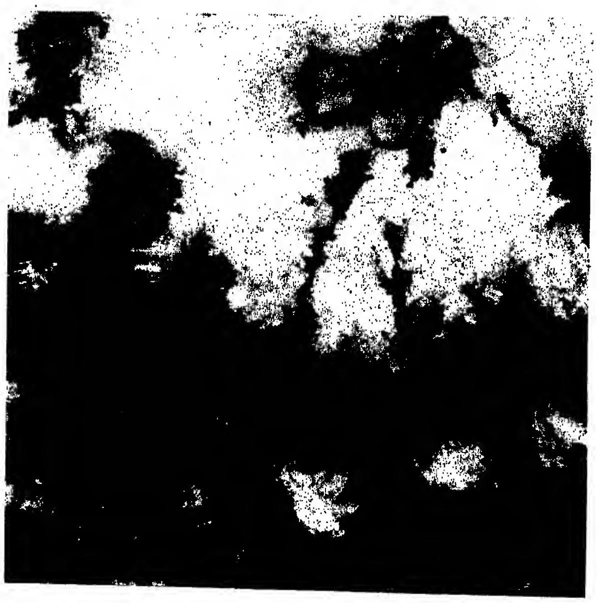

Plate XLIII.

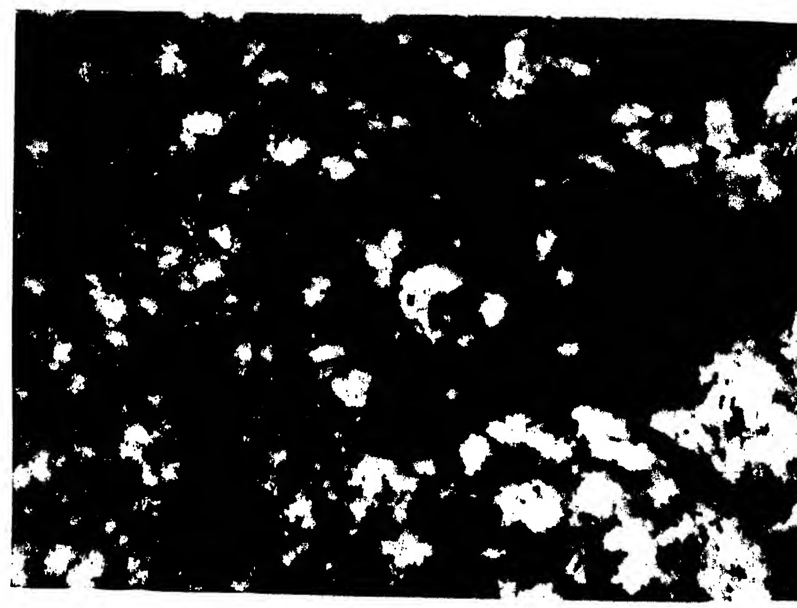

Plate XLIV.

Frost Crystals in the Stables. (*Natural size.*)

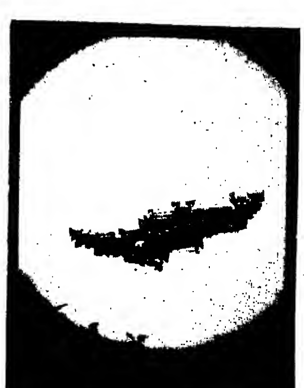

Plate XLV. (× 2½)

Plate XLVI.

Frost Crystals in the Stables. (*Natural size.*)

Photos by Wright.

Plate XLVII. (× 2½)

Plate XLVIII. (× 10)

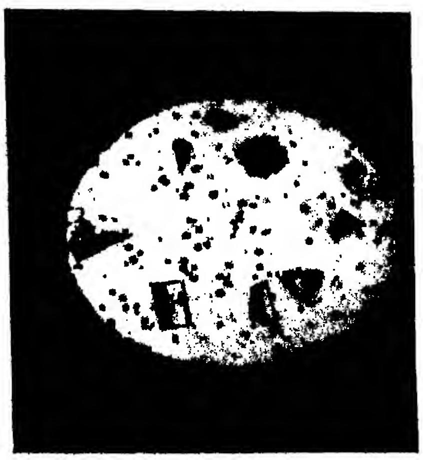

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Plate L. (× 40)

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Frost Crystals.

Plate LI.—Frost Crystals from Crevasse. (*Natural size.*)

Photos by Wright.

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Plate LII.—Crystals from a Winter Snowdrift. (*Natural size.*)
Page 72. *Photo by Wright.*

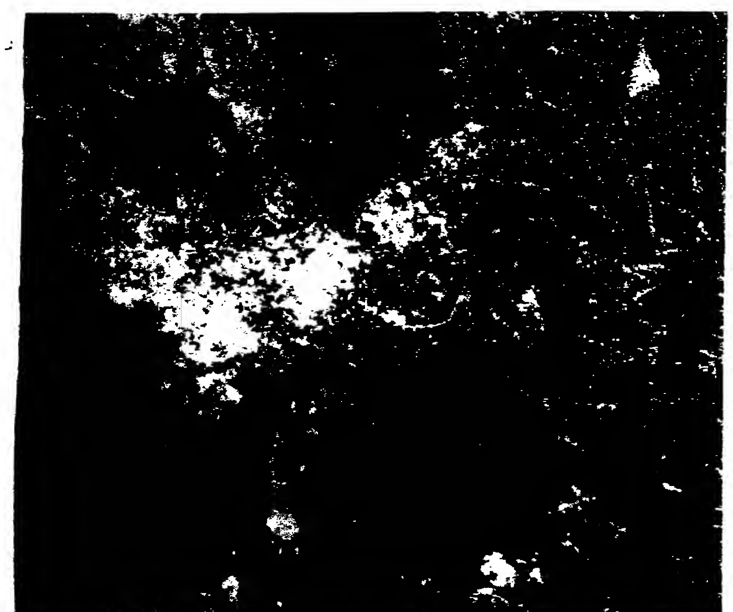

Plate LIII.—Crystals deposited on a wooden box embedded in a Winter Snowdrift. ($\times \frac{1}{2}$)
Page 72. *Photo by Wright.*

Plate LIV.—Crystals deposited on inner side of outer pane of a double window. (*Natural size.*)
Page 72. *Photo by Ponting.*

Plate LV.—Crystals formed on window pane.

Page 72. *Photo by Levick.*

Plate LVI.—Glacier Grains outlined by rubbing with lead pencil. (× ½)

Page 75. *Photo by Wright.*

Plate LVII.—Structure of Sea Ice outlined by rubbing with barograph ink—horizontal section. (*Natural size.*)

Page 75. *Photo by Wright.*

Plate LVIII.—Structure of Sea Ice outlined by rubbing with barograph ink. (*Natural size.*)

Page 75. *Photo by Wright.*

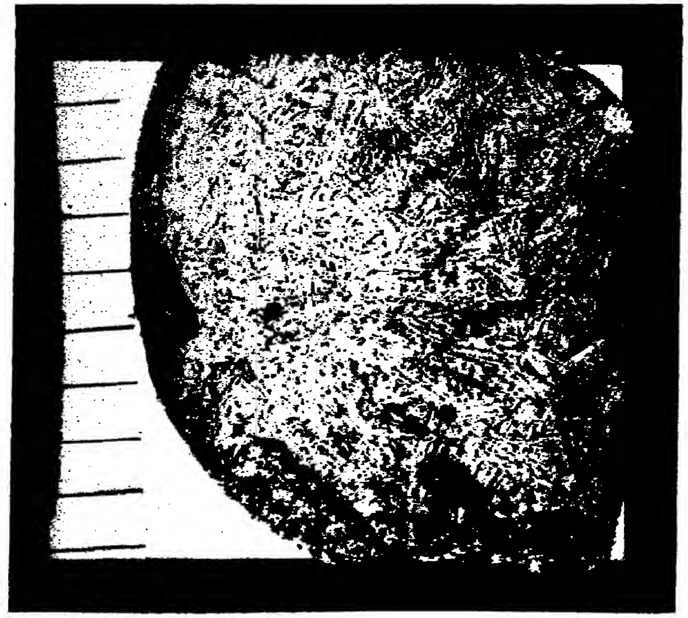

Plate LIX.—Structure of Frozen Seawater outlined by lightly brushing with soot. (*Natural size.*)

Plate LX.—Window pane figures outlined by lightly brushing with soot. (*Natural size.*)

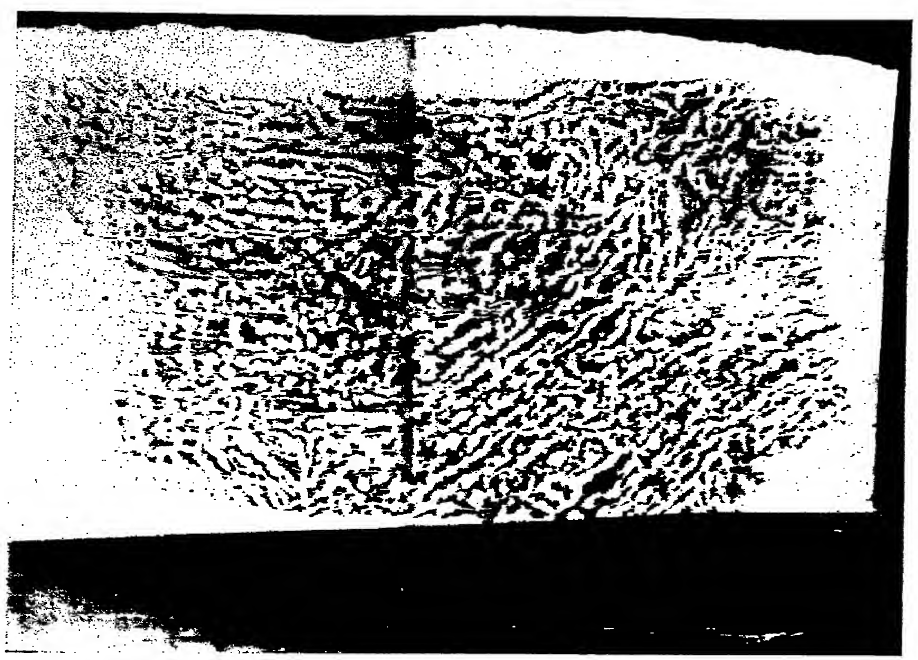

Plate LXI.—Rubbing of Arabesque Ice. (× ½)

Plate LXII.—Plasticine casts of crystals formed in an empty glacier stream bed. (*Natural size.*)

Photos by Wright.

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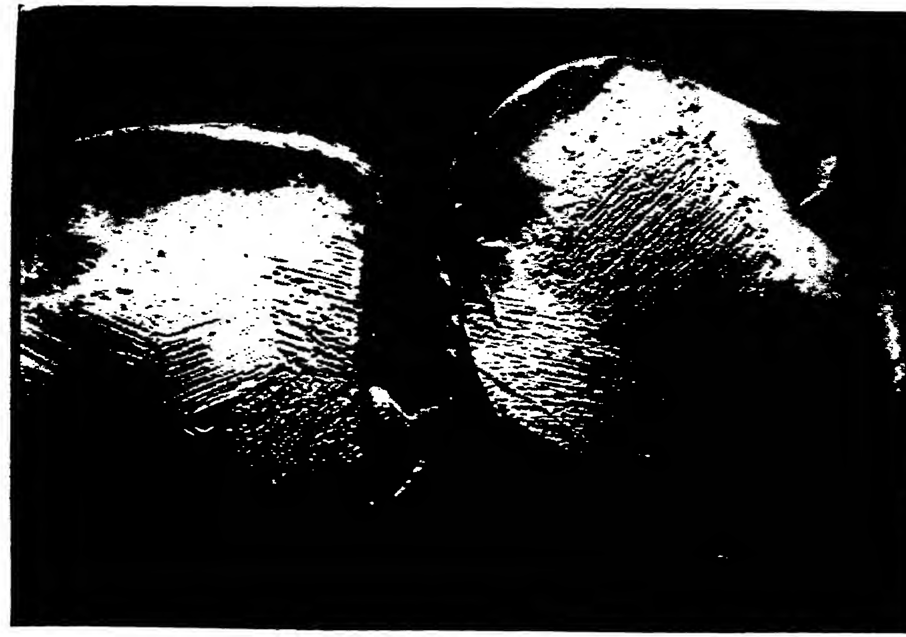

Plate LXIII.—Plaster of paris casts of ice structure in the bed of an empty glacier stream. (*Natural size.*)

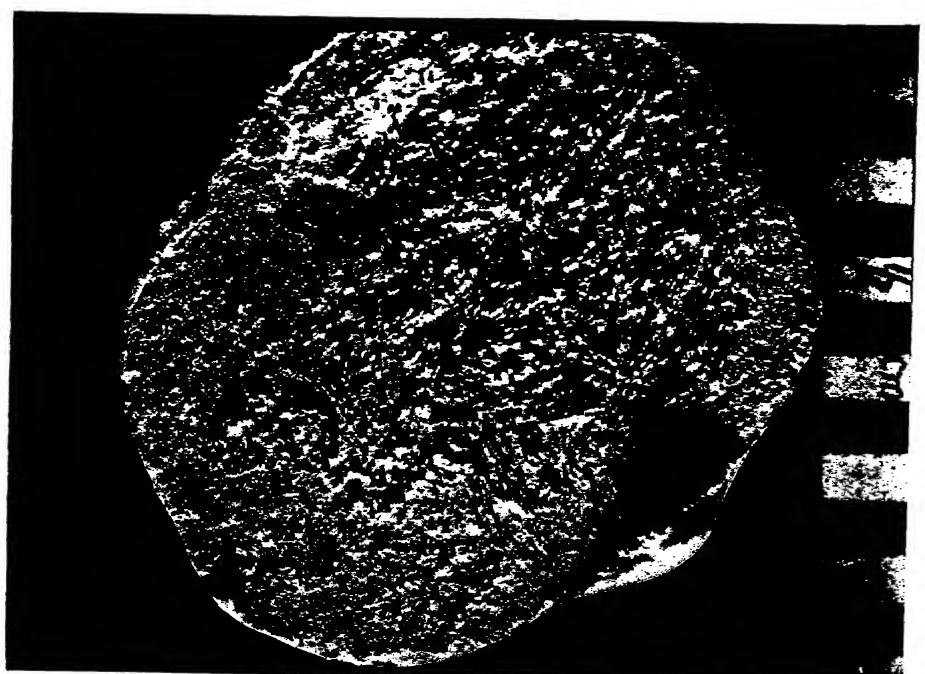

Plate LXIV.—Plaster of paris casts from horizontal section of Sea Ice. *Natural size.*)

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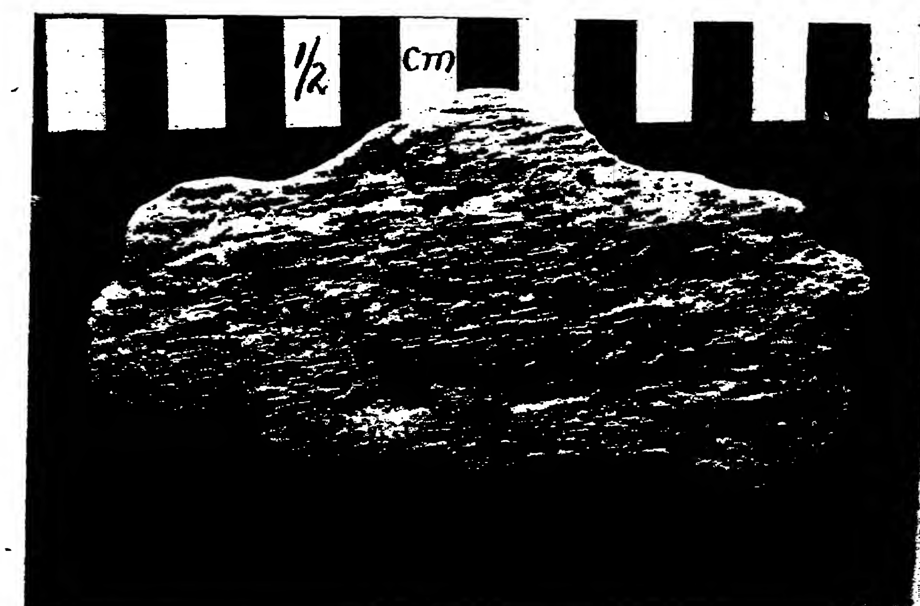


Plate LXV.—Plaster of paris casts from vertical section of Sea Ice. (*Natural size.*)

Photos by Wright.

Plate LXVI.—Crystals in artificially-frozen fresh water (outlined by hoar frost).
Page 77. (× ½) *Photo by Wright.*

Page 80. Plate LXVII.—Scum of Frazil Crystals on Sea.
Photo by Ponting.

Page 80. Plate LXVIII.—Frazil Crystals deposited on a rope.
Photo by Wright.

Plate LXIX.—Frazil Crystals deposited on seaweed.

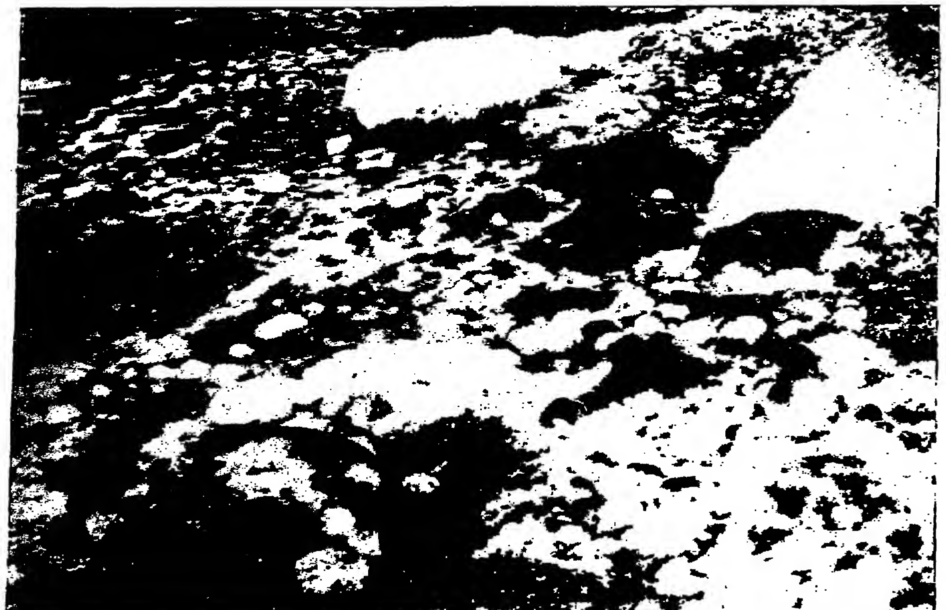
Page 81. *Photo by Lenick.*

Plate LXX.—Frazil Crystals deposited on a rope. (*Natural size.*)

Page 82. *Photo by Wright.*

Plate LXXI.—Frazil Crystals in bucket.

Page 84. *Photo by Wright.*



Page 84. Plate LXXII.—Ice-coated Boulders at Cape Adare. *Photo by Priestley.*

Plate LXXIII.—Crystals forming in freezing sea-water. ($\times \frac{2}{3}$)
Page 86. *Photo by Wright.*

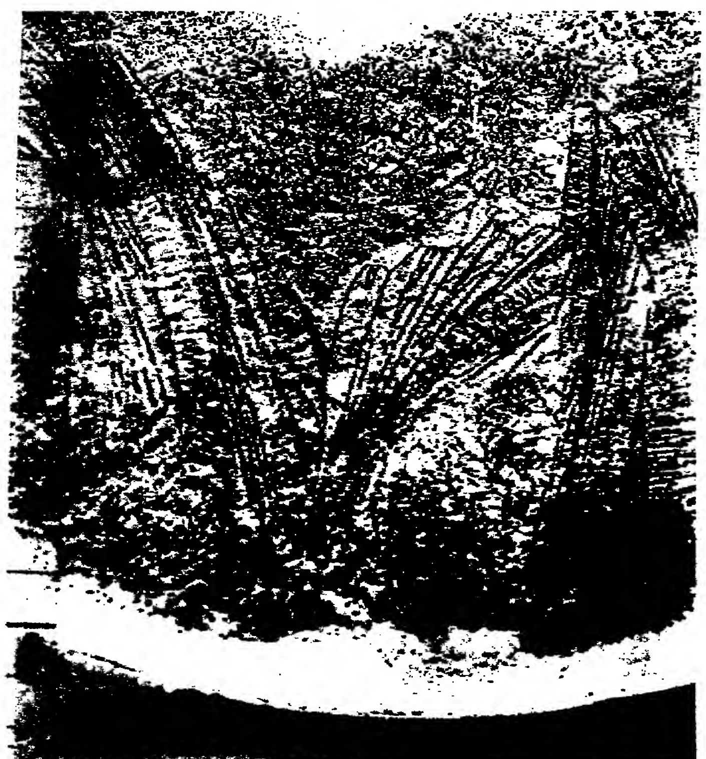


Plate LXXIV.—Structure of ice formed in contact with the metal dish containing it. ($\times \frac{1}{2}$)
Page 86. *Photo by Wright.*

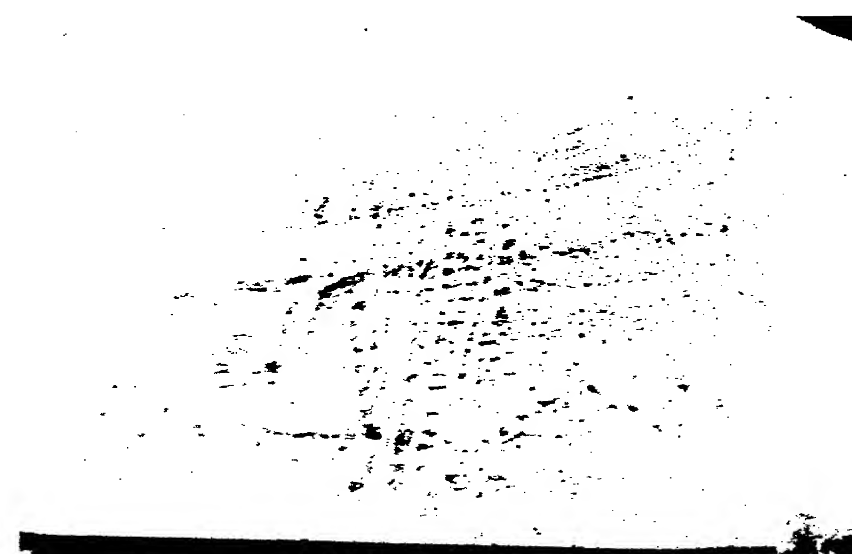


Plate LXXV.—Rubbing of surface of artificially-frozen sea-water. ($\times \frac{2}{3}$)
Page 88. *Photo by Wright.*

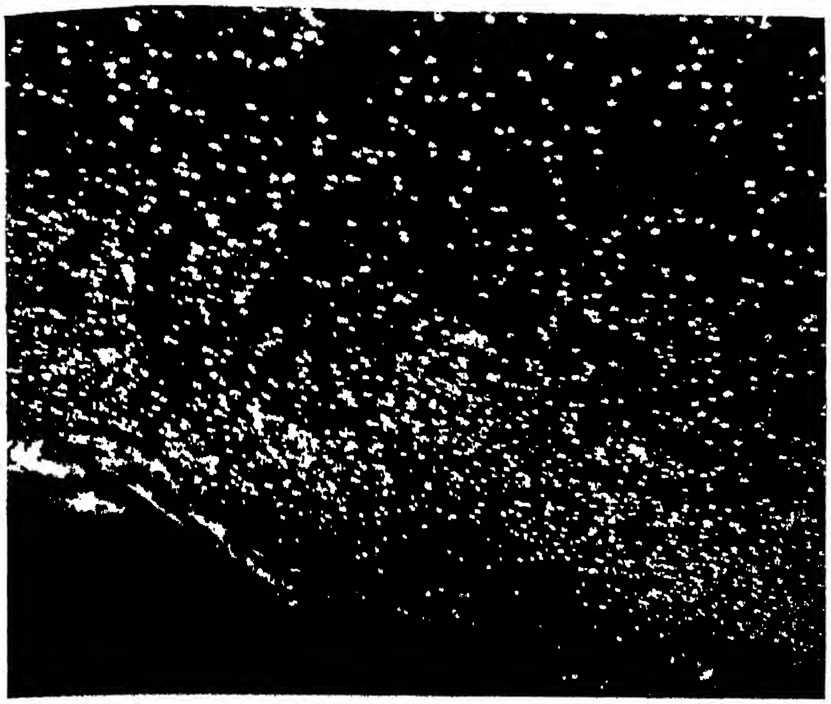


Plate LXXVI.—Newly-formed sea ice showing structure and variations in transparency of the constituent crystals. (The white spots are small ice flowers.)
Page 88. *Photo by Wright.*

Plate LXXVII.—Projecting blades on under surface of thick sea ic
Page 89. *Photo by Wright.*

Plate LXXVIII.—Ice column with annular growths.
Page 94. *Photo by Wright.*

Plate LXXIX.—Fresh-water icicle.
Page 95. *Photo by Priestley.*

Page 95. Plate LXXX.—Fresh-water icicles. *Photo by Levick.*

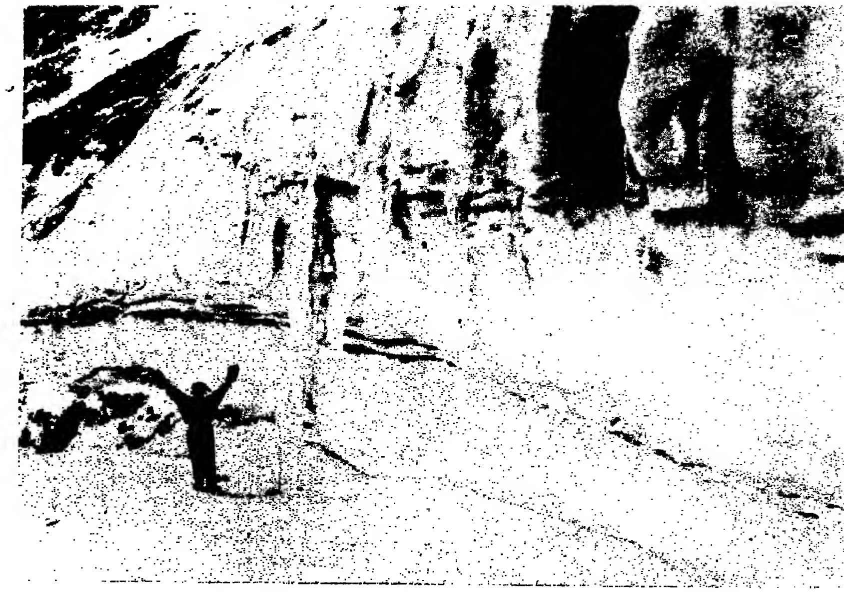


Plate LXXXI.—Broken pillar-forming icicle.

Page 95. *Photo by Levick.*

Plate LXXXII.—Icicles bent by gradual collapse of their support.

Page 96. *Photo by Wright.*

Plate LXXXIII.—Sharp-tipped salt-water icicles.

Page 96. *Photo by Levick.*

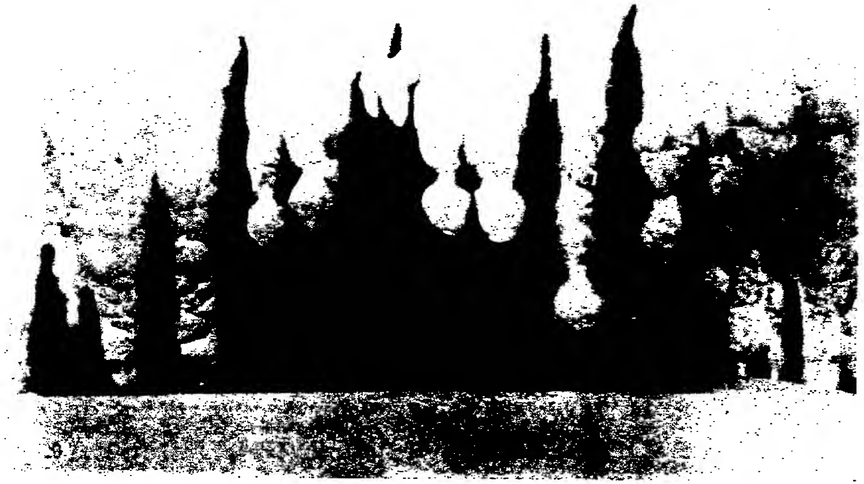


Plate LXXXIV.—Bulb-tipped icicles.

Plate LXXXV.—Bulb-tipped icicles.

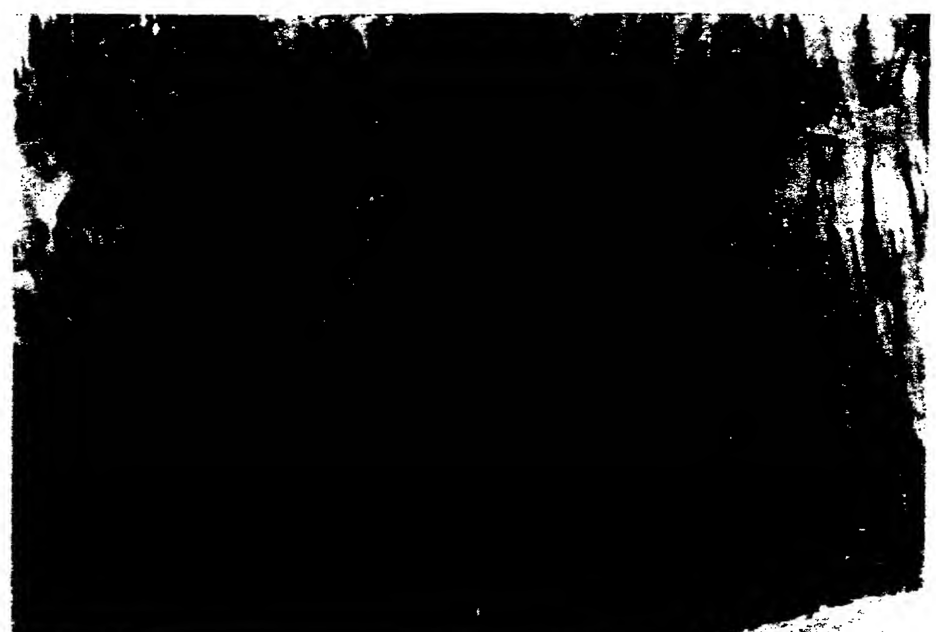


Plate LXXXVI.—Spray icicles.

Page 97. *Photos by Levick.*

Plate LXXXVII.—Spray icicles.

Page 97. *Photo by Levick.*

Plate LXXXVIII.—Icicles formed by the laving action of sea water.

Page 98. *Photo by Gran.*

Plate LXXXIX.—Composite icicles with accretions due to deposited hoar frost.

Page 98. *Photo by Levick.*

Page 98. Plate XC.—Section of icicle formed in successive storms.

Page 99. Plate XCI.—Foot stalactites.

Page 100. Plate XCII.—"Two-way" icicles. *Photos by Levick.*

Plate XCIII.—Club-shaped icicles.

Page 100. *Photo by Priestley.*

Plate XCIV.—Icicles of fantastic shape.

Page 100. *Photo by Wright.*

Plate XCV.—An Ice Dyke.

Page 108. *Photo by Levick.*

Plate XCVI.—Form of air inclusions in an Ice Dyke.
Page 108. *Photo by Lewick.*

Plate XCVII.—Normal bubbly Glacier Ice.
Pages 110 and 116. *Photo by Wright.*

Plate XCVIII.—A Breccia of Glacier-Ice in bubble-free ice.
Page 110. *Photo by Wright.*

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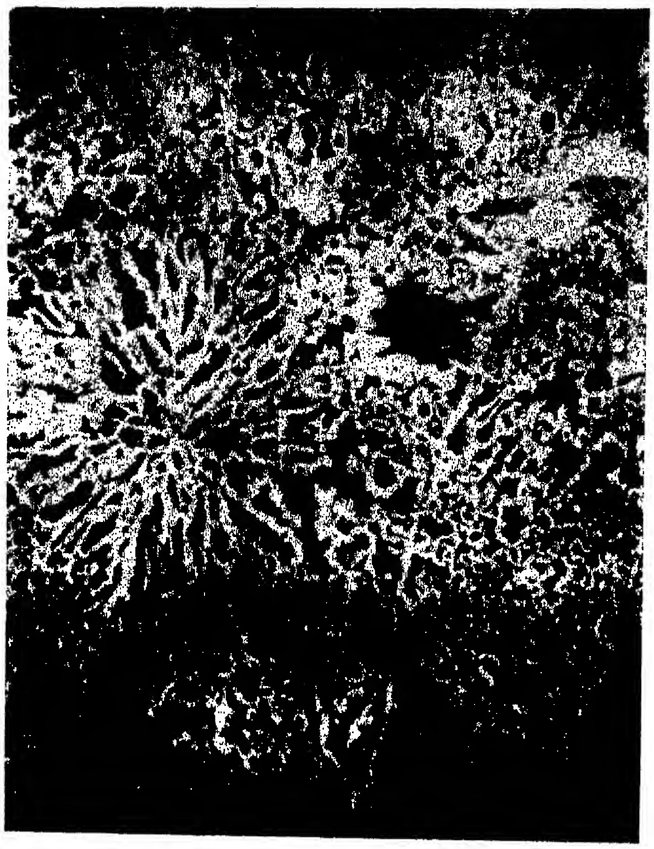

Plate XCIX.—Arabesque Ice

Page 112. *Photo by Priestley.*

Plate C.—Bubbles formed in Pond Ice from decay of vegetable matter during freezing.

Page 114. *Photo by Wright.*

Plate CI.—Elongated bubbles in Glacier Ice.

Page 115. *Photo by Wright.*

Plate CII.—Elongated bubbles in Glacier Ice (horizontal section).
Page 115. *Photo by Wright.*

Plate CIII.—Elongated bubbles in Glacier Ice (vertical section).
Page 115. *Photo by Wright.*

Plate CIV.—Compacted Snow.
Page 116. *Photo by Levick.*

Plate CV.—Névé.

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Photo by Levick.

Plate CVI.—Striated boulder of soft rock issuing from the Barne Glacier face. Conformable lines of silt-bearing ice are also visible.

Page 131.

Photo by Wright.

Plate CVII.—Highland-Ice Sheet (Robertson Bay).

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[*Photo by Levick*

Plate CVIII.—Highland-Ice Sheet on Ross Island. (Cape Royds is somewhat to the right but is not shown.)

Page 149. *Photo by Ponting.*

Plate CIX.—Highland-Ice Sheet on west bank of Beardmore Glacier.

Page 149. *Panorama by Wright.*

Plate CX.—Cwm Glacier (Robertson Bay).

Page 149. *Telephoto by Levick.*

Plate CXI.—Low-level Cwms at Glacier level (Beardmore Glacier).

Page 149. *Photo by Wright.*

Plate CXII.—An accumulation of Snowdrift-Ice which has become incorporated in the Icefoot (Robertson Bay).
Page 152. *Photo by Levick.*

Plate CXIII.—Snowdrift-Ice on Inexpressible Island (Terra Nova Bay).
Page 152. *Photo by Priestley.*

Plate CXIV.—Wall-sided diffluent from a sheet of Highland Ice (Terra Nova Bay area).
Page 153. *Photo by Priestley.*

Plate CXV.—Wall-sided Glacier of lobate form (Robertson Bay).
Page 153. *Photo by Levick.*

Plate CXVI.—The Wall-sided Double-curtain Glacier (Ferrar Glacier region).
Page 153. *Photo by Wright.*

Plate CXVII.—The Priestley Glacier, a valley glacier draining Continental-Ice.
Page 155. *Photo by Levick.*

Plate CXVIII.—The George Newnes Glacier, a valley Glacier draining Highland-Ice.
Page 155. *Photo by Levick.*

Page 157. Plate CXIX.—Panorama of Mackay Glacier Tongue *Panorama by Debenham*

Page 157. Plate CXX.—New Glacier, an Ice-Tongue in the Granite Harbour area. *Photo by Debenham.*

Plate CXXI.—Butter Point Piedmont-Ice.

Page 158. *Photo by Gran*

Plate CXXII.—Surface of Confluent-Ice Sheet. (Corner Glacier in the distance.)

Page 161. *Photo by Priestley.*

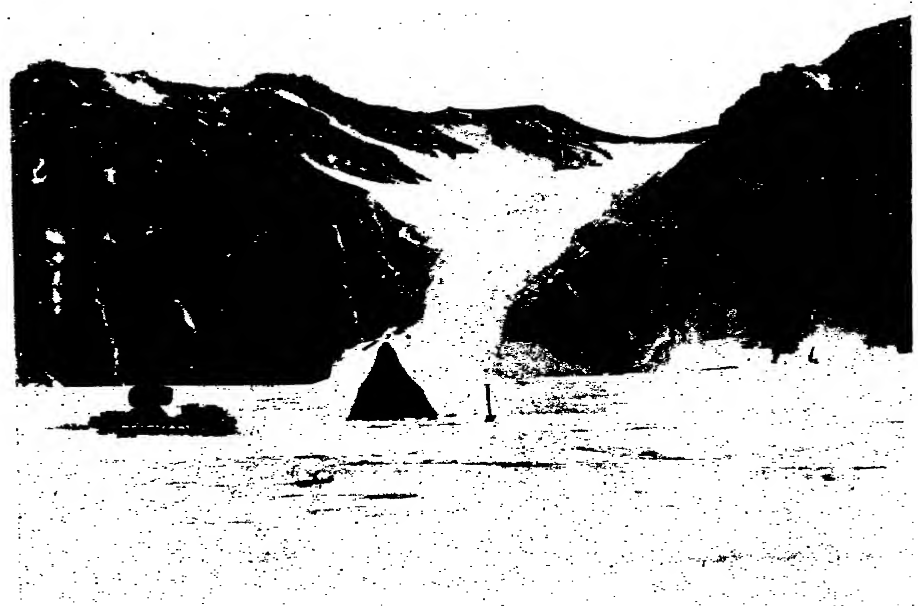

Plate CXXIII.—Small Glacier in Ferrar Glacier area showing typical talus.

Page 161. *Photo by Brocklehurst.*

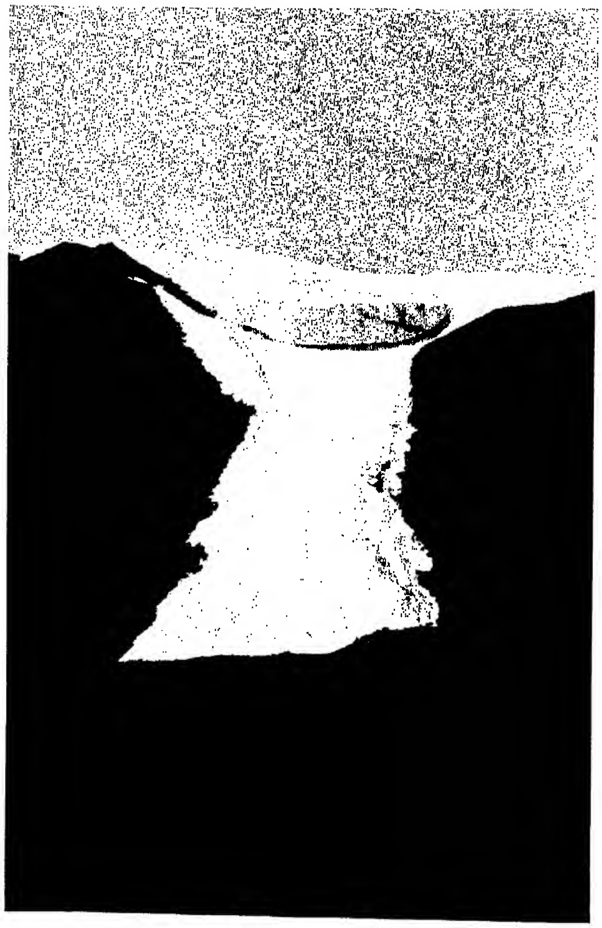

Plate CXXIV.—Glacier with Ice-Apron near Corner Glacier.
Page 161. *Photo by Priestley.*

Plate CXXV.—The Canada Glacier, an expanded foot Glacier in the Taylor Valley area.
Page 155. *Photo by Debenham.*

Plate CXXVI.—Highland-Ice Sheet on Ross Island (from top of Inaccessible Island).
Page 183. *Photo by Wright.*

Plate CXXVII.—Pressure rolls in a Glacier modified by ablation and thaw.
Page 102. *Photo by Priestley.*

Plate CXXVIII.—Warning Glacier Ice-Tongue (Robertson Bay).
Page 108. *Photo by Levick.*

Plate CXXIX.—Erebus Bay Ice-Tongue ("Glacier Tongue") from Turk's Head, showing "rolls," with Hut Point Peninsula behind.
Page 109. *Photo by Wright.*

Plate CXXX.—Barne Glacier Face.

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Photo by Wright.

Plate CXXXI.—Nameless Glacier Face.

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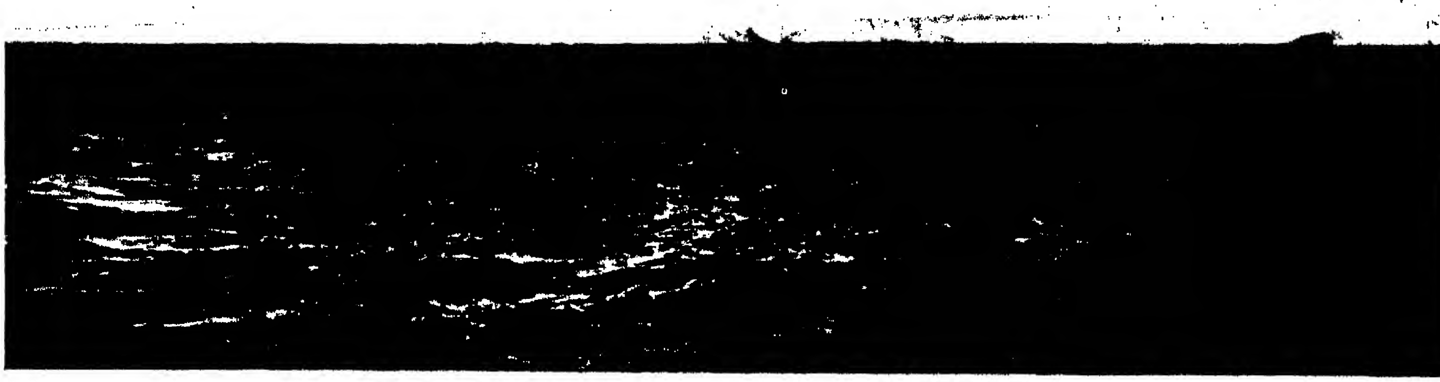
Photo by Levick.

Plate CXXXII.—The Ross Barrier, near Amundsen's Winter Quarters, showing the "Fram."

Page 206.

Photo by Priestley.



Page 206. Plate CXXXIII.—The Ross Barrier. *Photo by Ponting.*

Plate CXXXIV.—Railroad Moraine on the Campbell-Priestley Confluent-Ice.
Page 225. *Photo by Priestley.*

Page 225. Plate CXXXV.—Lateral Moraine on the Koettlitz Glacier. *Photo by Debenham.*

Plate CXXXVI.—Scattered Moraine on the Campbell-Priestley Confluent-Ice.

Page 225. *Photo by Levick.*

Plate CXXXVII.—Scattered Moraine on the Campbell-Priestley Confluent-Ice.

Page 225. *Photo by Priestley.*

Plate CXXXVIII. —Railroad Moraine on Boomerang Glacier.

Page 225. *Photo by Levick.*

Plate CXXXIX.—Lateral Moraine of Corner Glacier.

Page 225. *Photo by Priestley.*

Plate CXL.—Lateral Moraine of Corner Glacier.

Page 225. *Photo by Priestley.*

Plate CXLI.—Moraine sunk bodily beneath the general level of the Ice (Terra Nova Bay area).

Page 226. *Photo by Levick.*

Plate CXLII.—Snowdrifts in lee of Boulders.

Page 226. *Photo by Taylor.*

Plate CXLIII.—Raised Medial Moraine of the Dugdale-Murray Glacier.

Page 227. *Photo by Levick.*

Plate CXLIV.—Raised Moraine on the Campbell-Priestley Confluent-Ice.

Page 227. *Photo by Levick.*

Plate CXLV.—Glacier Table.

Page 223. *Photo by Priestley.*

Plate CXLVI.—Terminal Moraine of Hobbs Glacier (Koettlitz Glacier area).

Page 231. *Photo by Wright.*

Plate CXLVII.—Structure of water-sorted Mud in Terminal Moraine of Hobbs Glacier.

Page 232. *Photo by Wright.*

Plate CXLVIII.

Plate CXLIX.

Page 233. Two small masses of Snowdrift-Ice north of Warning Glacier, showing well-marked silt bands. *Photos by Levick.*

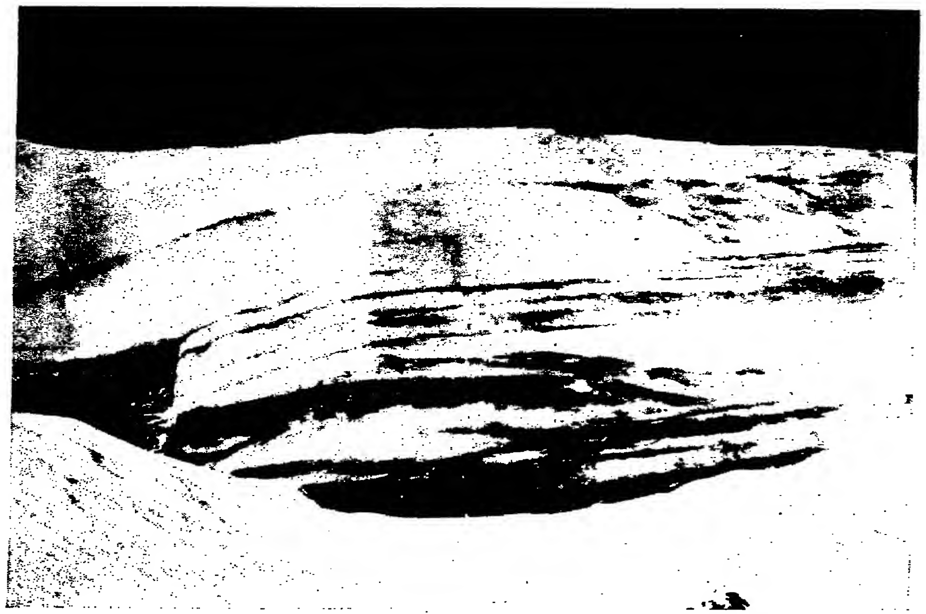


Plate CL.—Silt bands apparently crossing one another in Barne Glacier face.
Page 234. *Photo by Wright.*

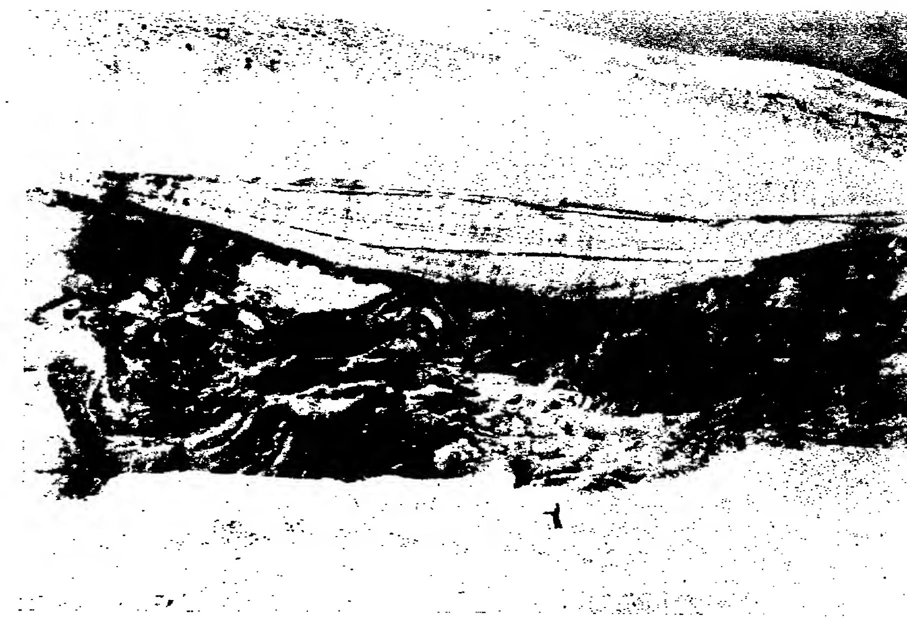


Plate CLI.—Unconformity in Warning Glacier (Robertson Bay).
Page 235. *Photo by Levick.*

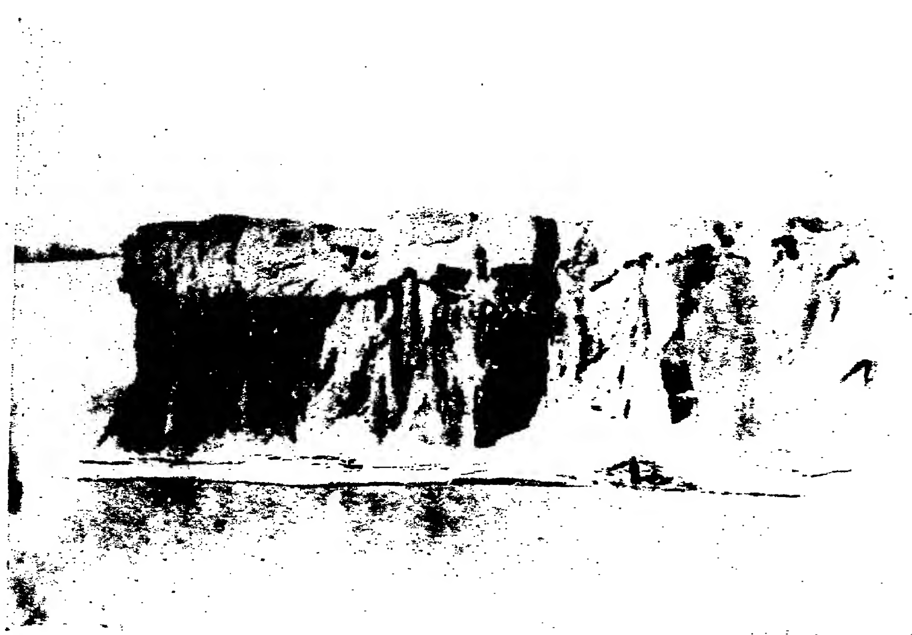


Plate CLII.—Unconformity in Glacier-Ice. True Ice lies both above and below the unconformity, and the present surface of the Glacier is now one of ablation (George Newnes Glacier, Robertson Bay).
Page 235. *Photo by Levick.*

Plate CLIII.—Unconformities in Glacier-Ice betrayed by the presence of concentration silt bands (Warning Glacier, Robertson Bay).
Page 235. *Photo by Levick.*

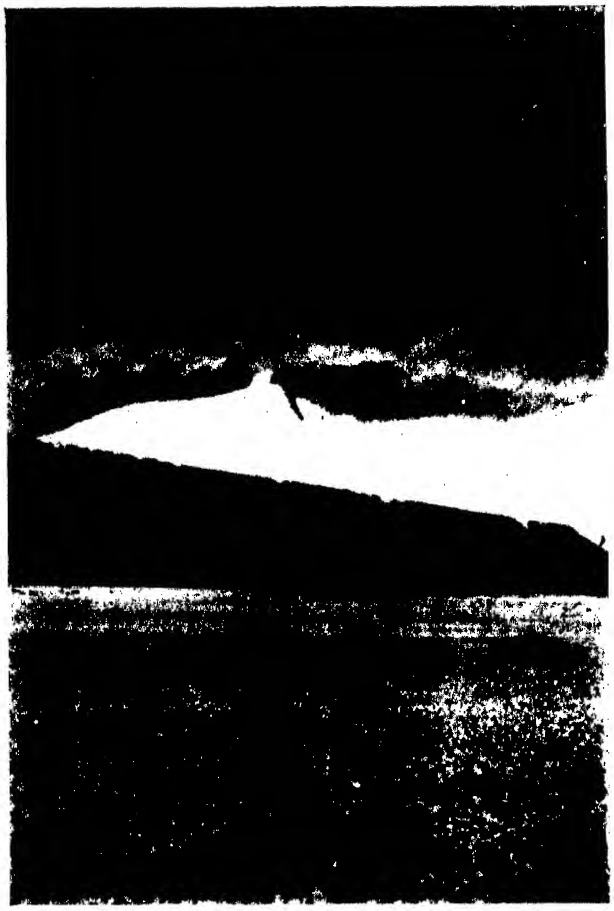


Plate CLIV.—Barne Glacier, showing unconformity. Crevasses chiefly confined to lower strata (Ross Island).
Page 235. *Photo by Wright.*

Plate CLV.—Iceberg with double unconformity. Note series of Cre
confined to lower strata only (Robertson Bay, October, 1911).
Page 235. *Photo by*

Plate CLVI.—Concentric Stratification round exposed rock bluff shown by silt bands (Root of Warning Glacier, Robertson Bay).
Page 237. *Photo by Levick*

Plate CLVII.—Re-cemented Crevasses or Ice-Dykes (Warning Glacier).
Page 239. *Photo by Levick.*

Plate CLVIII.—Re-cemented Crevasses or Ice-Dykes (Warning Glacier).
Page 239. *Photo by Levick.*

Plate CLIX.—Curved Air-tubes in a block of nearly clear ice (Lateral Moraine of Koettlitz Glacier).
Page 240. *Photo by Wright.*

Plate CLX.

Plate CLXI.

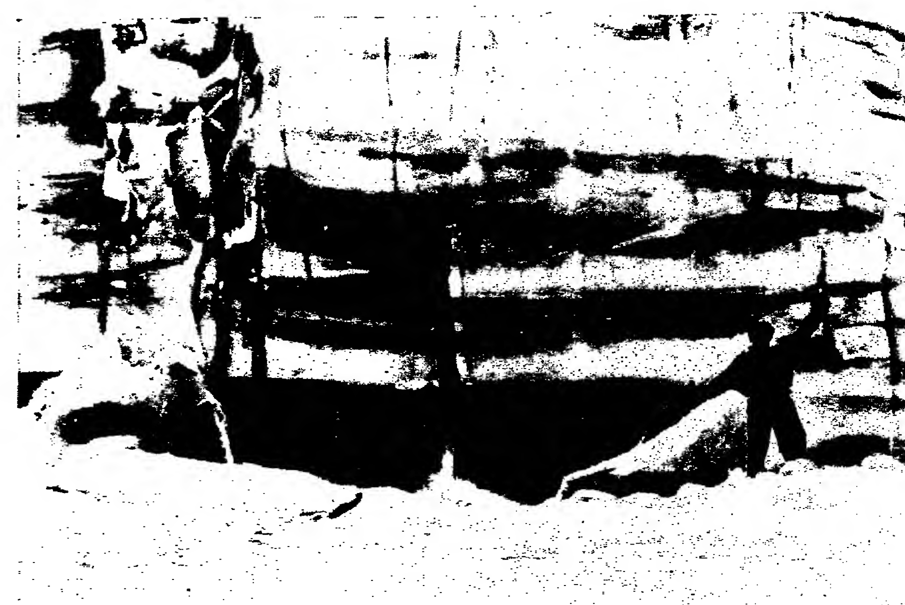
Page 240.

Horizontal Bluebands.

Photos by Levick.

Plate CLXII.

Plate CLXIII.



Page 250.

Faulting and overthrust in Glacier-Ice, shown by dislocation of silt bands (Warning Glacier).

Photos by Levick.

Plate CLXIV.—An Overfold in Glacier-Ice (Warning Glacier).

Page 250. *Photo by Levick.*

Plate CLXV.—Overfold in Glacier-Ice (Barne Glacier).

Page 250. *Photo by Wright.*

Plate CLXVI.—Longitudinal Pressure Ridges in the Koettlitz Glacier (opposite Heald Island).

Page 251. *Photo by Wright.*

Plate CLXVII.—Ice falls on Ross Island (between Turk's Head and Cape Evans).
Page 254. *Photo by Wright.*

Plate CLXVIII.—Ice falls (Terra Nova Bay region).
Page 254. *Photo by Priestley.*

Plate CLXIX.—Regular transverse Crevasses at the entrance of the Priestley Glacier (Terra Nova Bay area).
Page 254. *Photo by Priestley.*

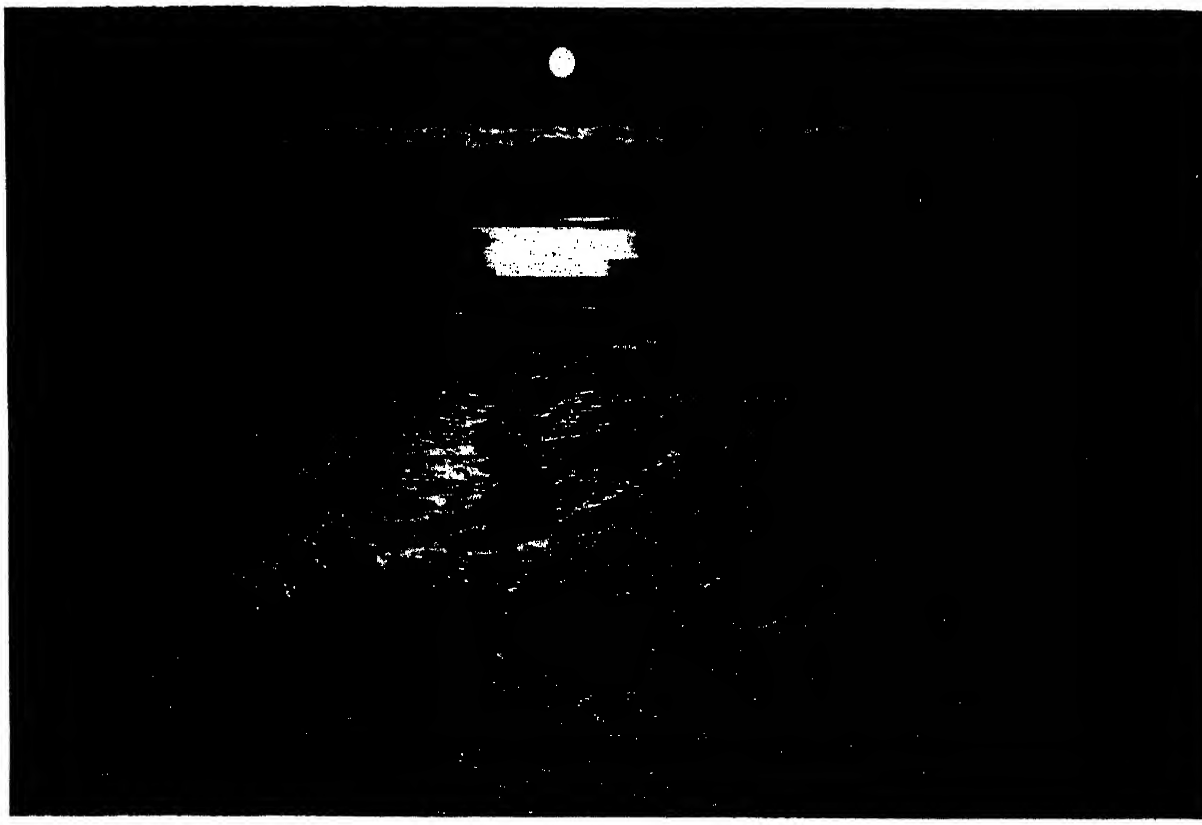


Plate CLXX.—Bridged Crevasse on almost stagnant Barne Glacier

Page 254.

Photo by Ponting.

Plate CLXXI.—A Hidden Crevasse.

Page 254.

Photo by Priestley.

Plate CLXXII.—Pinnacle of Ice on face of Warning Glacier (Robertson Bay).

Page 254.

Photo by Levick.

Plate CLXXIII.—Snow-filled Crevasses exposed on the Terminal Face of a Glacier (Robertson Bay area).

Page 257. *Photo by Priestley.*

Plate CLXXIV.—Crevasses on the Priestley Glacier modified by time and thaw.

Page 257. *Photo by Priestley.*

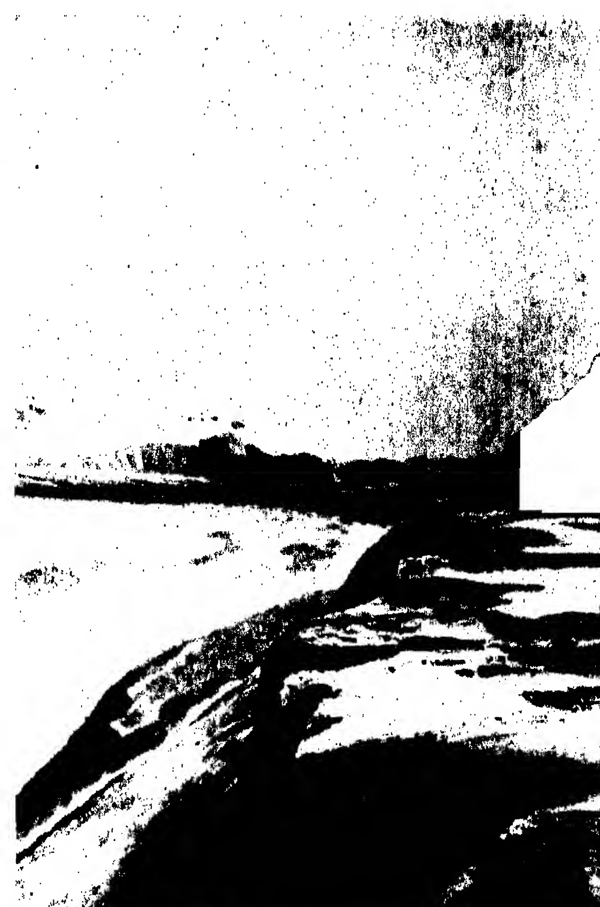


Plate CLXXV.—A Barranca.

Page 257. *Photo by Priestley*

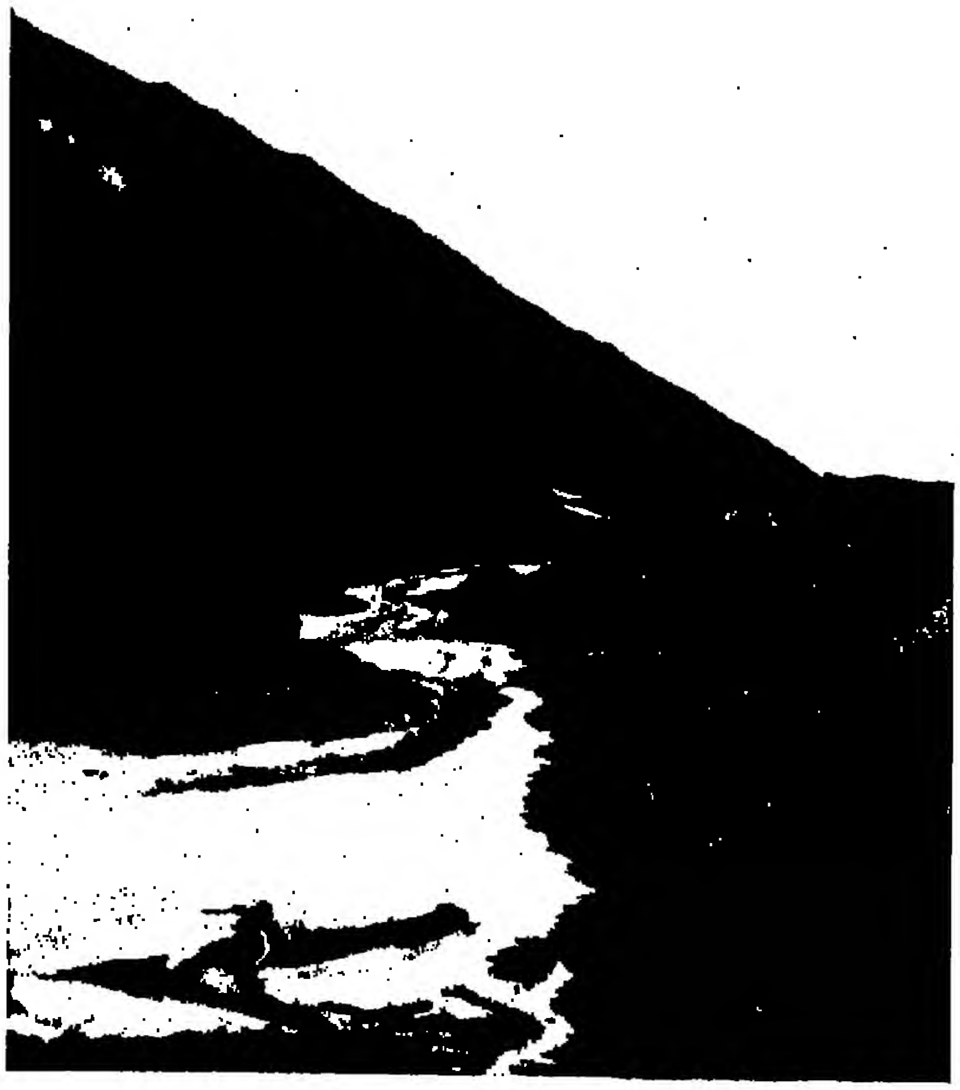


Plate CLXXVI.—Corner Glacier Lateral Moraine, showing side of Glacier.

Page 250. *Photo by Priestley.*

Plate CLXXVII.—Vertical Wall of Barne Glacier.

Page 260. *Photo by Wright.*

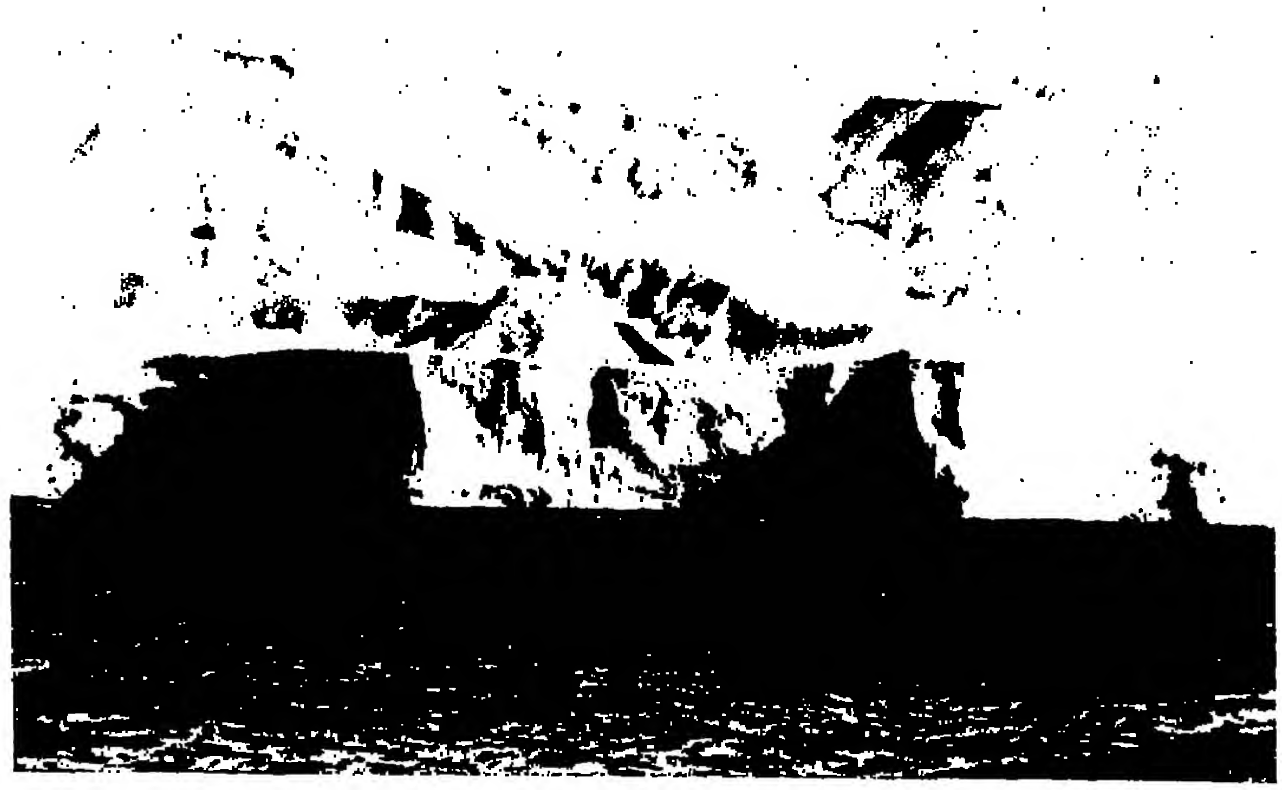


Plate CLXXVIII.—Vertical Glacier Face.

Page 260. *Photo by Levick.*

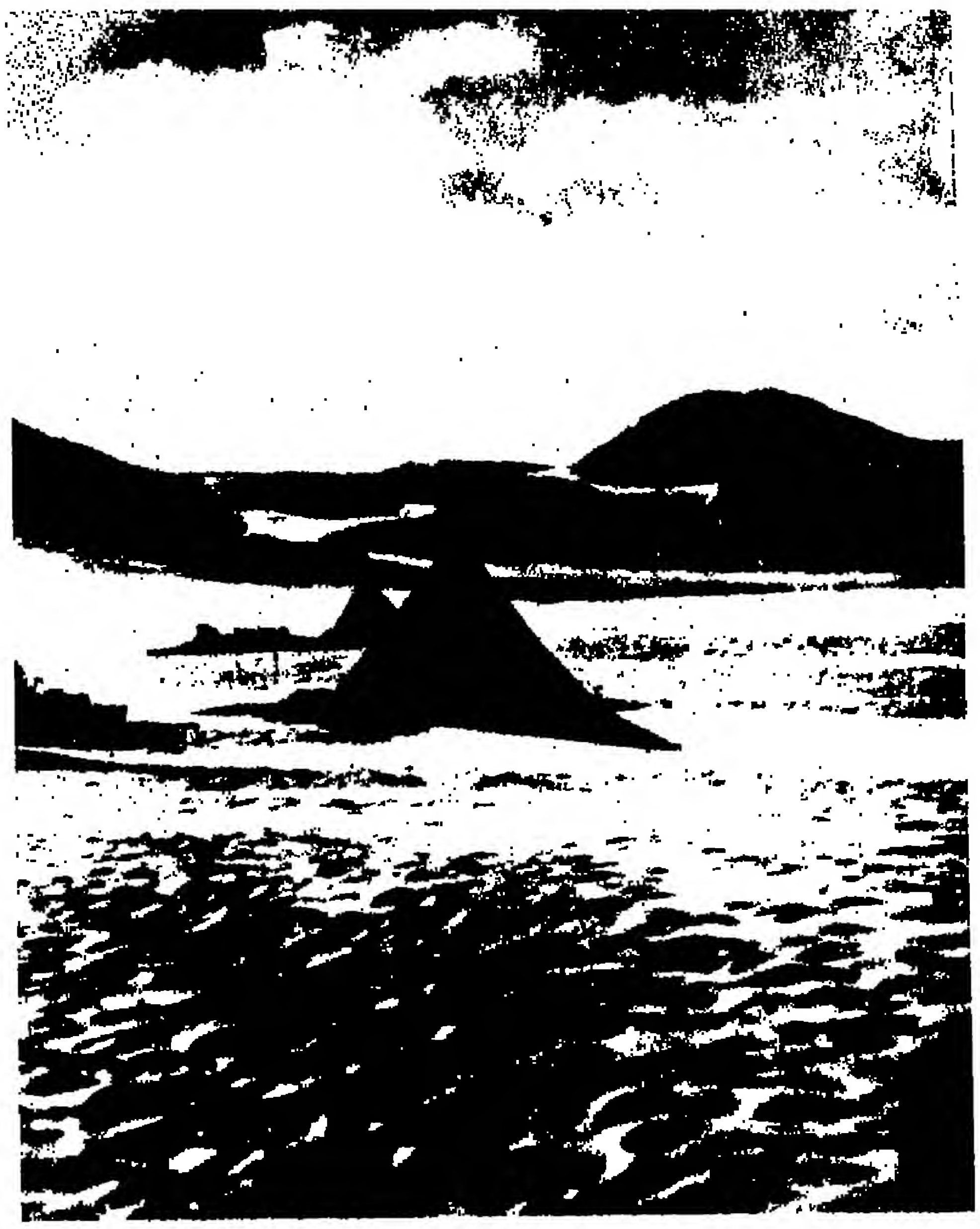


Plate CLXXIX.—Ablation Pits (top of Beardmore Glacier, Buckley Island behind).

Page 271. *Photo by Wright.*

Plate CLXXX.—Ablation Pits and deserted stream beds (Koettlitz Glacier).

Page 271. *Photo by Wright.*

Plate CLXXXI.—Ploughshare Ablation Pits and deserted stream channels (Koettlitz Glacier).

Page 271. *Photo by Wright.*

Plate CLXXXII.—Ploughshare Ablation Pits.

Page 271. *Photo by Wright.*

Plate CLXXXIII.—Weathering of rock from ice, due chiefly to wind action.
Page 276. *Photo by Wright.*

Plate CLXXXIV.—Weathering of sand from ice, due to wind action.
Page 276. *Photo by Wright.*

Plate CLXXXV.—Radiation Pit round a boulder.
Page 279. *Photo by Levick.*

Plate CLXXXVI.—Thaw Stream in Radiation Gully on the Ferrar Glacier.
Page 279. *Photo by Brocklehurst, in 1908.*

Plate CLXXXVII.—Thaw Channels on Glacier Face.
Page 279. *Photo by Levick.*

Plate CLXXXVIII.—Radiation Gully round Mount Hooper (Ross Island).
Page 279. *Photo by Priestley.*

Plate CLXXXIX.—Glacier Stream.
Page 281. *Photo by Priestley.*

Plate CXC.

Plate CXCI.

Pinnacled Ice (Koettlitz Glacier).

Page 283. *Photos by Debenham.*

Plate CXCII.—Ablation on northern side of Ice Ridges (Koettlitz Glacier, just below Heald Nunatak).

Page 285. *Photo by Wright.*

Plate CXCIII.—Lateral Moraine of Koettlitz Glacier and underlying ice.

Page 287. *Photo by Debenham.*

Plate CXCIV.—Ice beneath Lateral Moraine of Koettlitz Glacier (only a thin veneer of rock debris overlies the solid ice).

Page 287. *Photo by Debenham.*

Plate CXCV.—Penitent Ice (side of Ferrar Glacier).

Page 288. *Photo by Wright.*

Plate CXCVI.—Pinnacled Ice on an Icefoot.

Page 288. *Photo by Levick.*

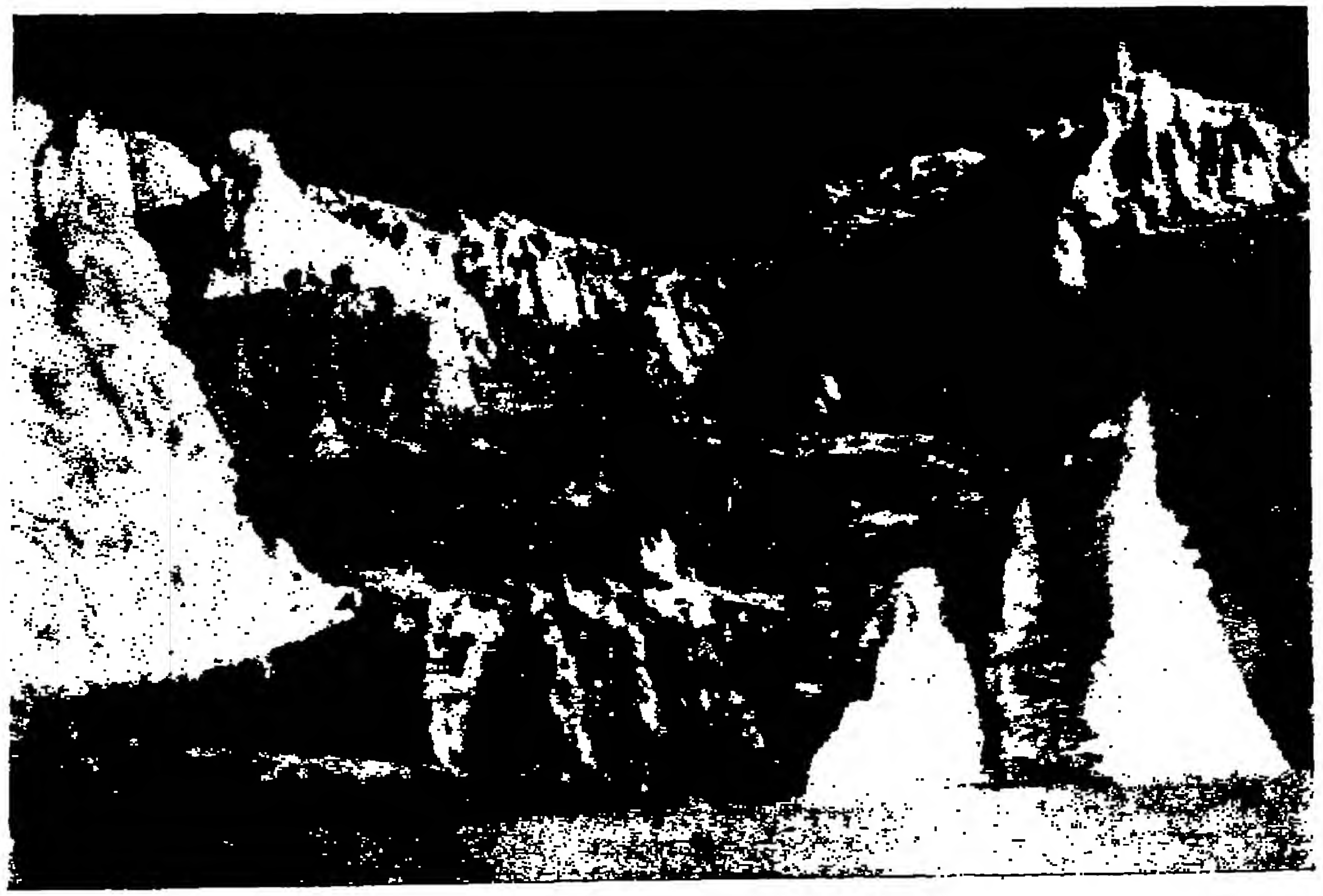


Plate CXCVII.—Pinnacled Ice.

Page 288. *Photo by Gran.*

Plate CXCVIII.—Deserted Stream Channel (Corner Glacier).

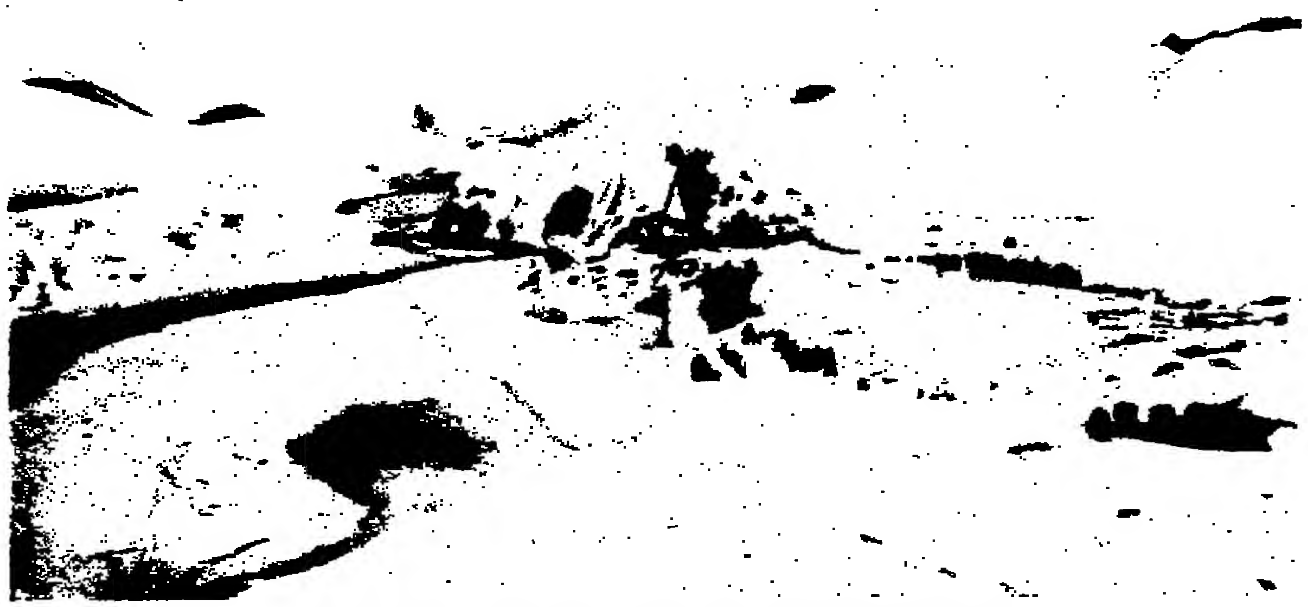
Page 289. *Photo by Priestley.*

Plate CXCIX.—Glacier Lake.

Page 290. *Photo by Priestley.*

Plate CC.—Lakes in a Glacier Moraine (Corner Glacier).

Page 290. *Photo by Priestley.*



Page 291. Plate CCI.—Glacier Lake by Medial Moraine. *Photo by Levick.*

Page 297. Plate CCII.—Tidal Platform at North Bay, Cape Evans. *Photo by Wright.*

Page 299. Plate CCIII.—Growth of Icefoot chiefly at the top (Cape Evans). *Photo by Ponting.*

Page 300. Plate CCIV.—Ice-foot with vertical edge (Cape Adare). *Photo by Levick.*

Page 300. Plate CCV.—Growth of Ice-foot at the surface of the water. *Photo by Debenham.*

Plate CCVI.—Ice-foot in process of dissolution (Cape Royds).

Page 301.

Photo by Debenham.

Plate CCVII.—Last stage in dissolution of Ice-foot (Cape Evans).

Page 302.

Photo by Ponting.

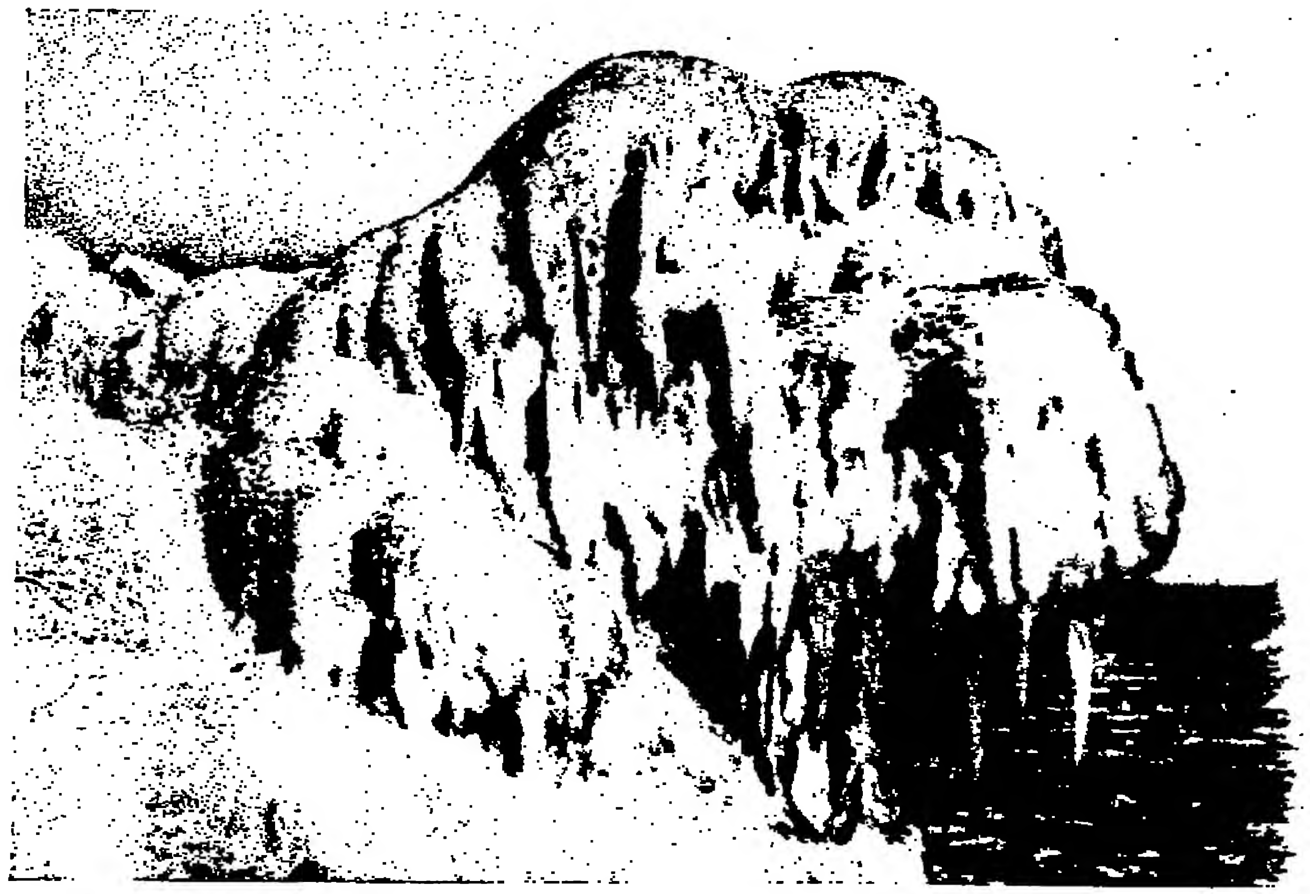


Plate CCVIII.—Storm Ice-foot (Cape Adare).

Page 304. *Photo by Levick.*

Plate CCIX.—Storm Ice-foot (Cape Adare).

Page 304. *Photo by Levick*

Plate CCX.—Stranded Floe Ice-foot (Cape Adare).

Page 307. *Photo by Levick.*

Plate CCXI.—Stranded Floe Ice-foot (Cape Adare).

Page 307. *Photo by Levick.*

Plate CCXII.—Ice-foot on a tilted berg.
Page 309. *Photo by Levick.*

Plate CCXIII.—Bed of gravel incorporated in Ice-foot (Cape Adare).
Page 310. *Photo by Levick.*

Plate CCXIV.—Boulders on the beach coated with Ice (Cape Adare).
Page 311. *Photo by Levick.*

Plate CCXV.—A wall of small rounded pieces of Brash-Ice.
Page 312. *Photo by Levick.*

Plate CCXVI.—Small stranded floes on the beach at Cape Adare.
Page 312. *Photo by Levick.*

Plate CCXVII.—Swan Ice on Cape Adare Ice-foot.
Page 313. *Photo by Priestley.*

Plate CCXVIII.—Swan Ice on Cape Adare Ice-foot.
Page 313. *Photo by Priestley.*

Plate CCXIX.—Growth of tidal platform filling up spaces between stranded floes.
Page 313. *Photo by Lerick.*

Plate CCXX.—Beds of gravel thrown on lower portions of Ice-foot.
Page 313. *Photo by Lerick.*

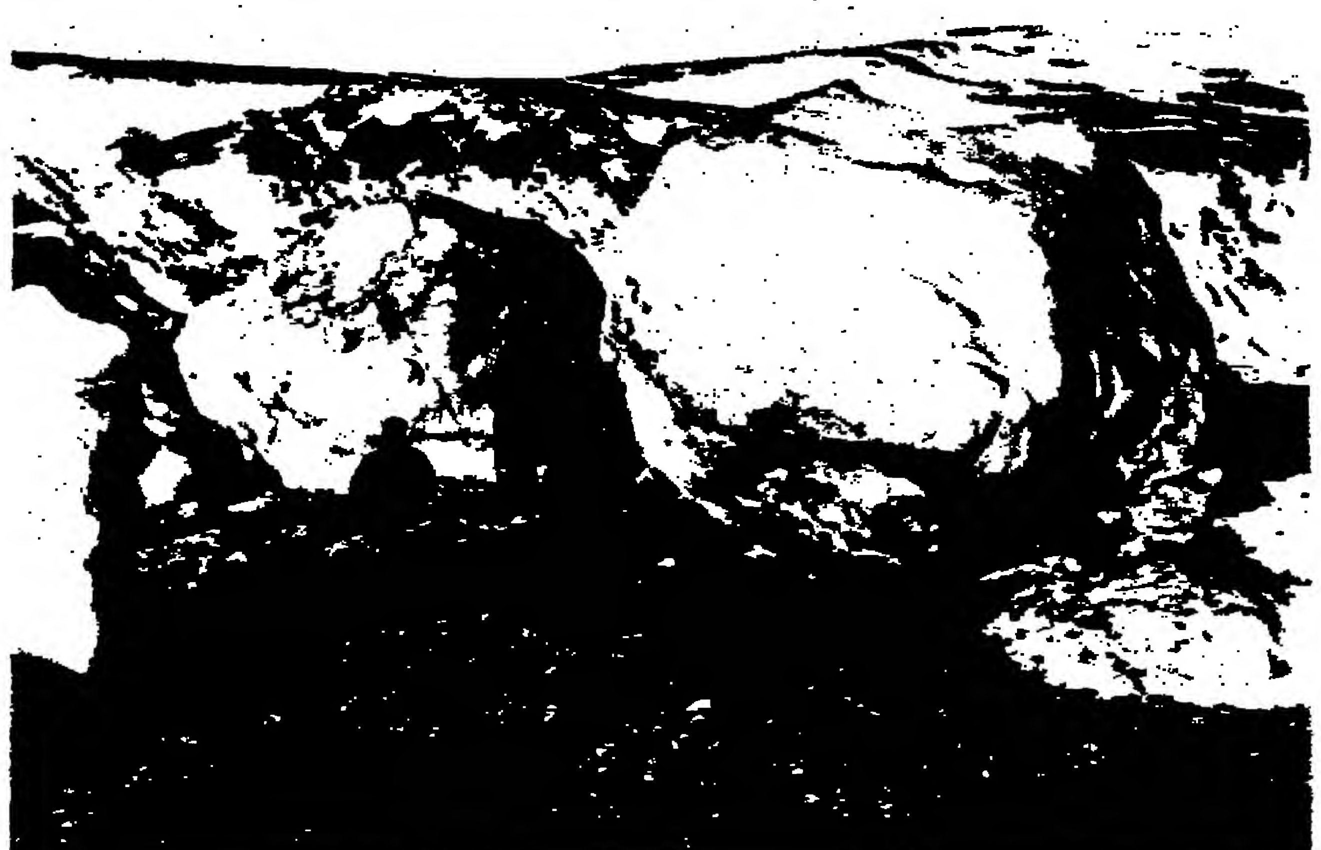


Plate CCXXI.—Ice boulders hurled above high-water mark by gales.
Page 314. *Photo by Lerick.*

Plate CCXXII.—Tidal Platform of great width (Terra Nova Bay).
Page 315. *Photo by Priestley.*

Plate CCXXIII.—Spray Ice-foot only a few yards wide.

Page 315. *Photo by Levick.*

Plate CCXXIV. Tidepole Cove (Cape Adare).

Page 318 *Photo by Levick.*

Plate CCXXV.—An Ice Block split by temperature change.

Page 320. *Photo by Levick.*

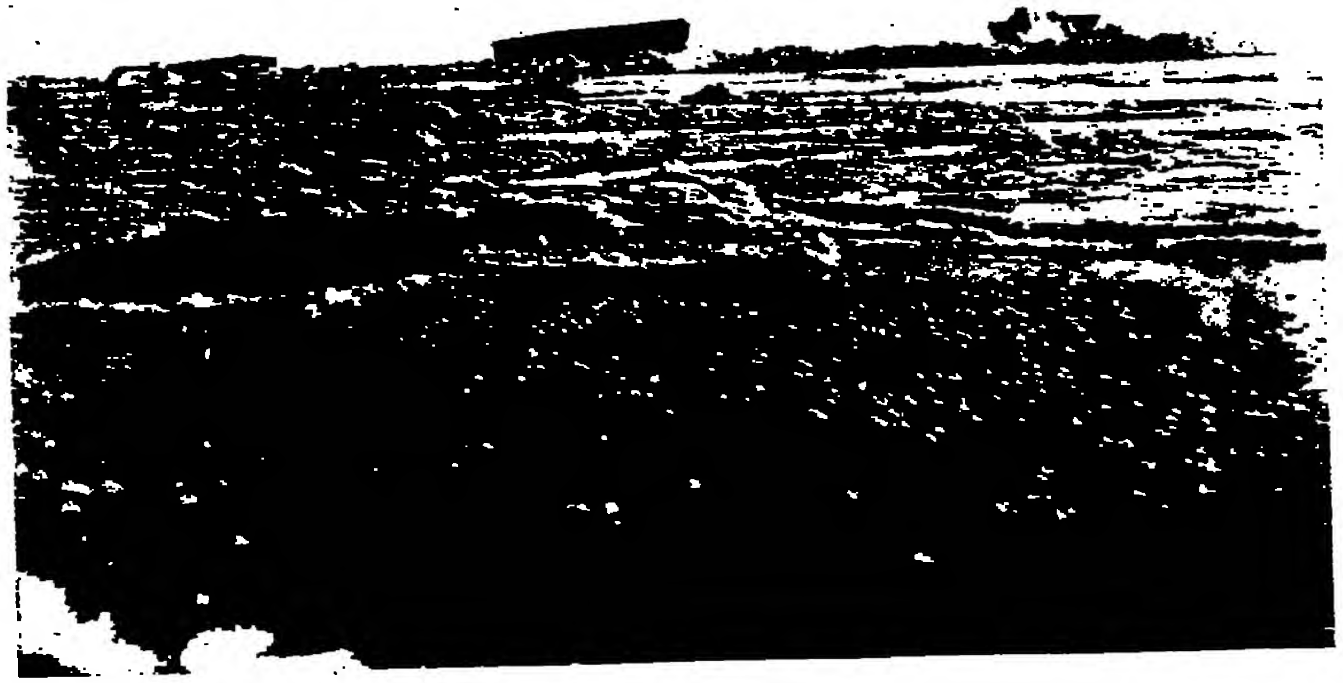


Plate CCXXVI.—Sheet of young " black " Ice in foreground.

Photo by Lerick.

Page 325.

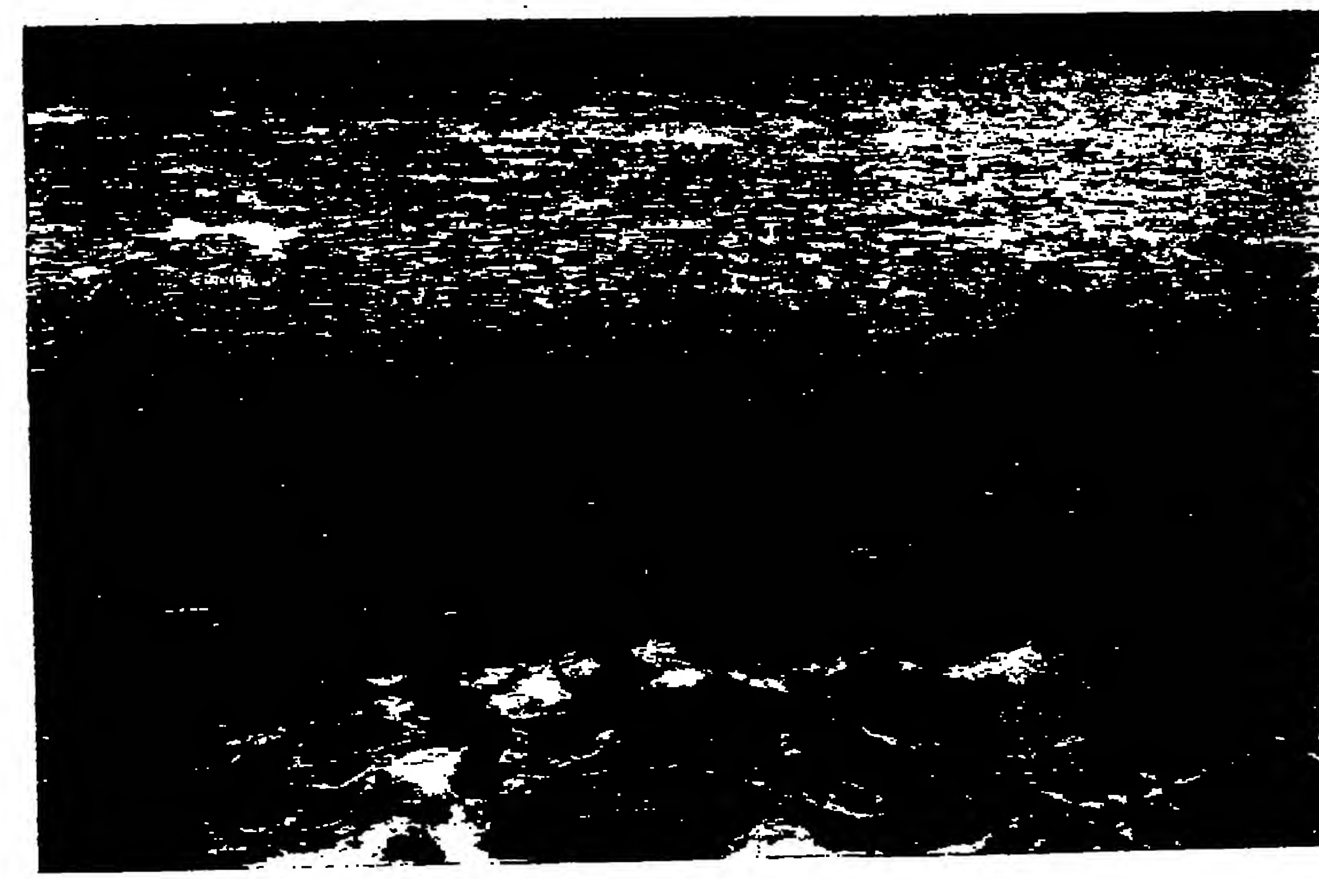


Plate CCXXVII.—Sheet of new Ice broken up and ridged by a slight swell.

Photo by Lerick.

Page 326.

Plate CCXXVIII.—Pancake-Ice.

Photo by Lerick.

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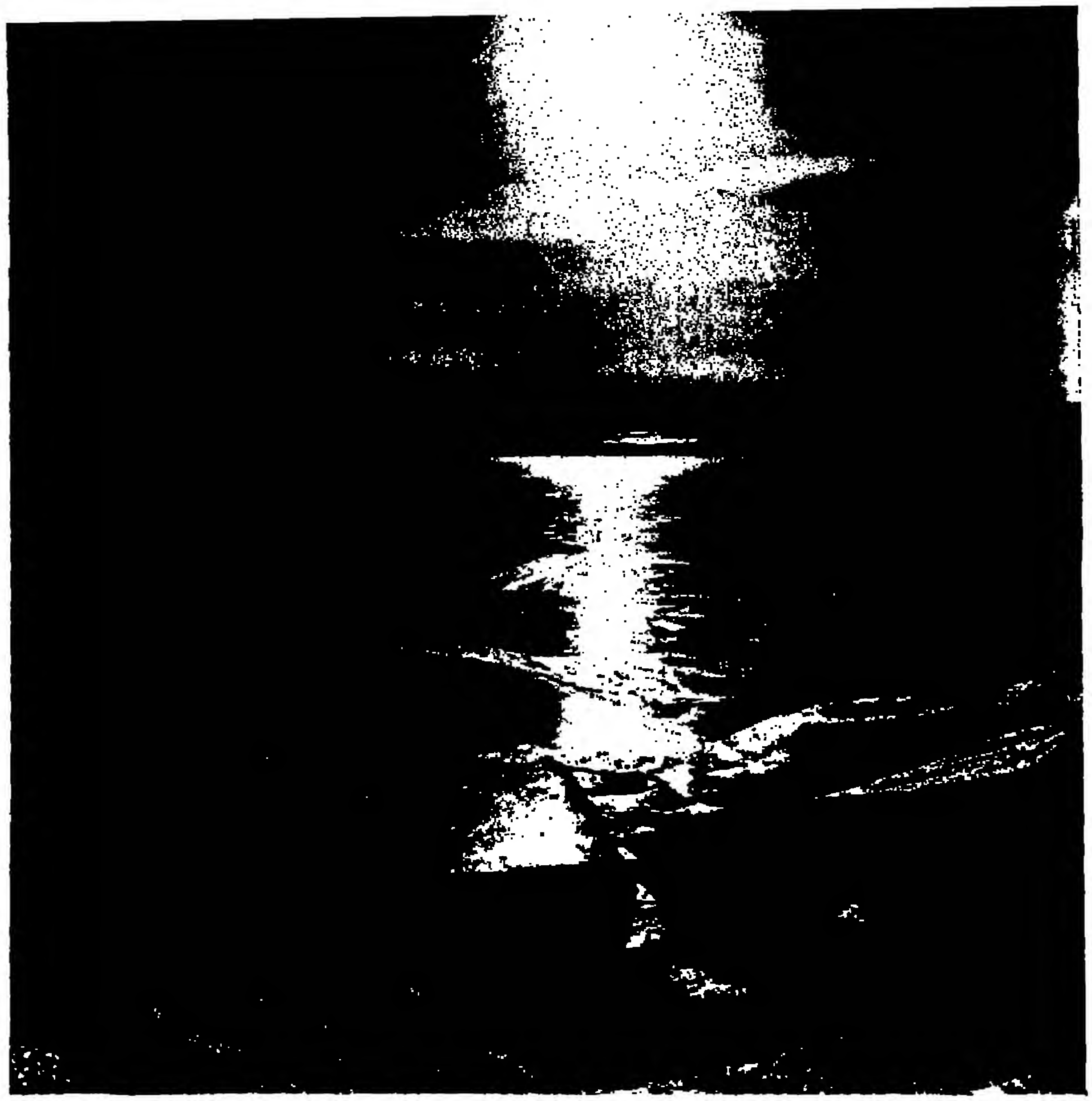


Plate CCXXIX.—Lines of drift Snow floating on the sea.

Page 326. *Photo by Ponting.*

Plate CCXXX.—Showing the method of formation of compound Pancake Ice.

Page 326. *Photo by Ponting.*

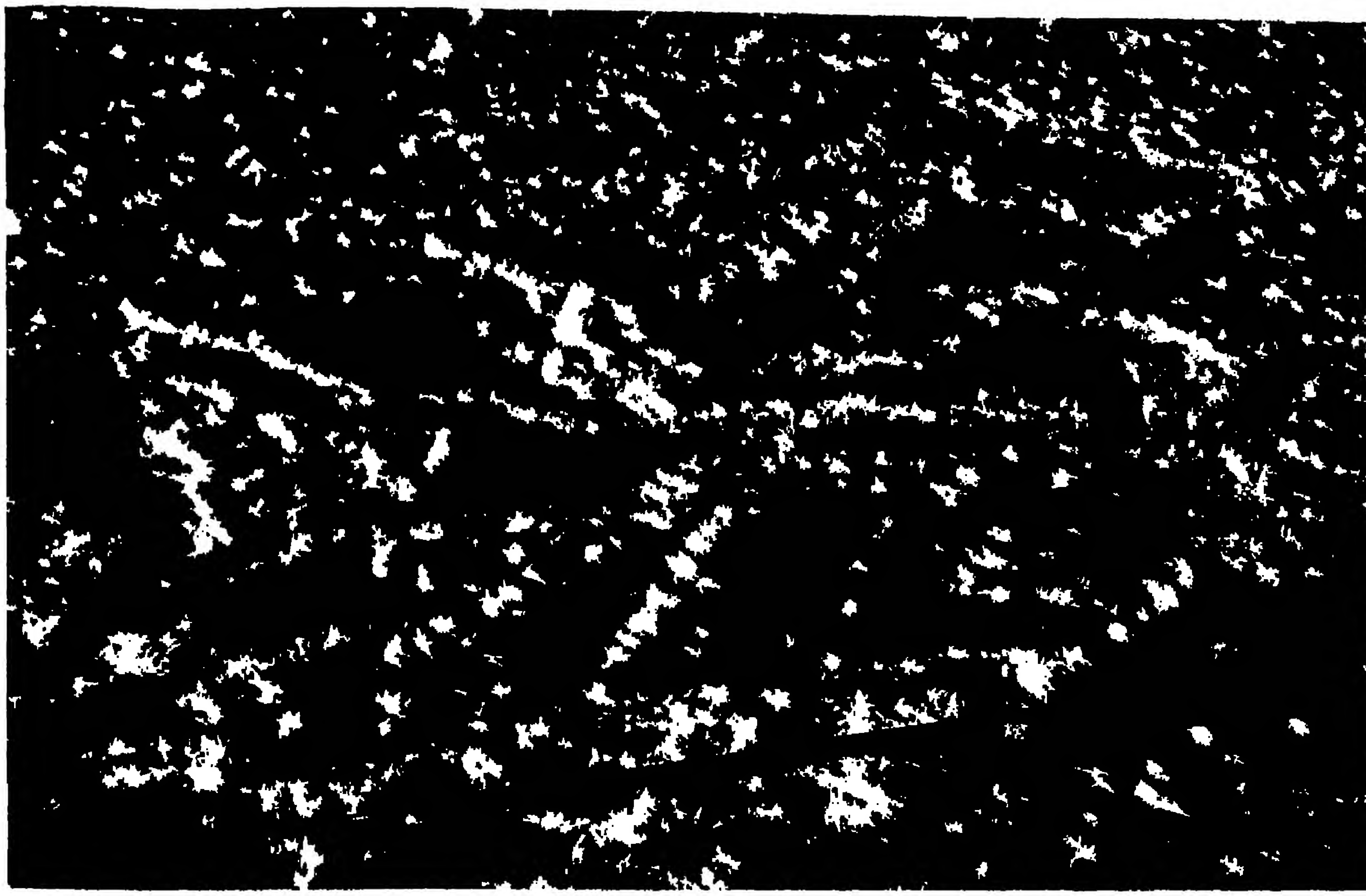


Plate CCXXXI.—Ice Flowers formed on new Sea Ice.

Page 339.

Photo by Debenham.

Plate CCXXXII.—Bending of young Sea Ice under pressure (Drain-pipe Ice).

Page 342.

Photo by Levick.

Plate CCXXXIII.—The effect of pressure upon thin Sea Ice.

Page 343.

Photo by Debenham.

Plate CCXXXIV.—Ridges and Troughs parallel to the shore formed by pressure in old Sea Ice (McMurdo Sound).

Page 344.

Photo by Wright.

Plate CCXXXV.—Pressure Ridge at Cape Adare.

Page 344.

Photo by Levick.

Plate CCXXXVI.—Pressure Ridge due to temperature changes in Sea Ice. *Photo by Ponting.*

Page 346.

Plate CCXXXVII.—Effect of pressure on new Sea Ice (Ice Slates). *Photo by Priestley.*

Plate CCXXXVIII.—Pressure Ridge composed of small blocks of Sea Ice less than 1 foot thick (Cape Adare). *Photo by Levick.*

Page 348.

Page 348. Plate CCXXXIX.—Pressure Ridge at Cape Royds (Ross Island). *Photo by Debenham.*

Plate CCXL.—Shear Crack leading to Mackay Ice-Tongue due to the forward movement of the Tongue.

Page 352. *Photo by Debenham.*

Plate CCXLI.—Blocks of Sea Ice lying on the top of an Iceberg.

Page 354. *Photo by Priestley.*

Page 360. Plate CCXLII.—Small Waterhole in Sea Ice off Cape Adare. *Photo by Levick.*

Plate CCXLIII.—Large Waterhole at Cape Adare covered with New Ice. *Photo by Levick.*
Page 360.

Page 367. Plate CCXLIV.—Summer Waterhole formed off the Barne Glacier. *Photo by Ponting.*

Plate CCXLV.—Undercutting at the edge of Fast-Ice.

Page 368.

Photo by Ponting.

Plate CCXLVI.—Dispersion of Rotten-Ice.

Page 370.

Photo by Ponting.

Page 370. Plate CCXLVII.—Dispersion of Fast-Ice by sea currents. *Photo by Lerick.*

Page 377. Plate CCXLVIII.—Pressure Floe, illustrating growth above the surface due to flooding by sea water. *Photo by Priestley.*

Photo by Ponting.

Page 393.

Plate CCL.—Level-Ice just after breaking.

Photo by Ponting.

Page 393.

Plate CCLI.—Typical Hummocky and Level-Ice Floes.

Photo by Ponting.

Plate CCLII.—A Field of Pack-Ice

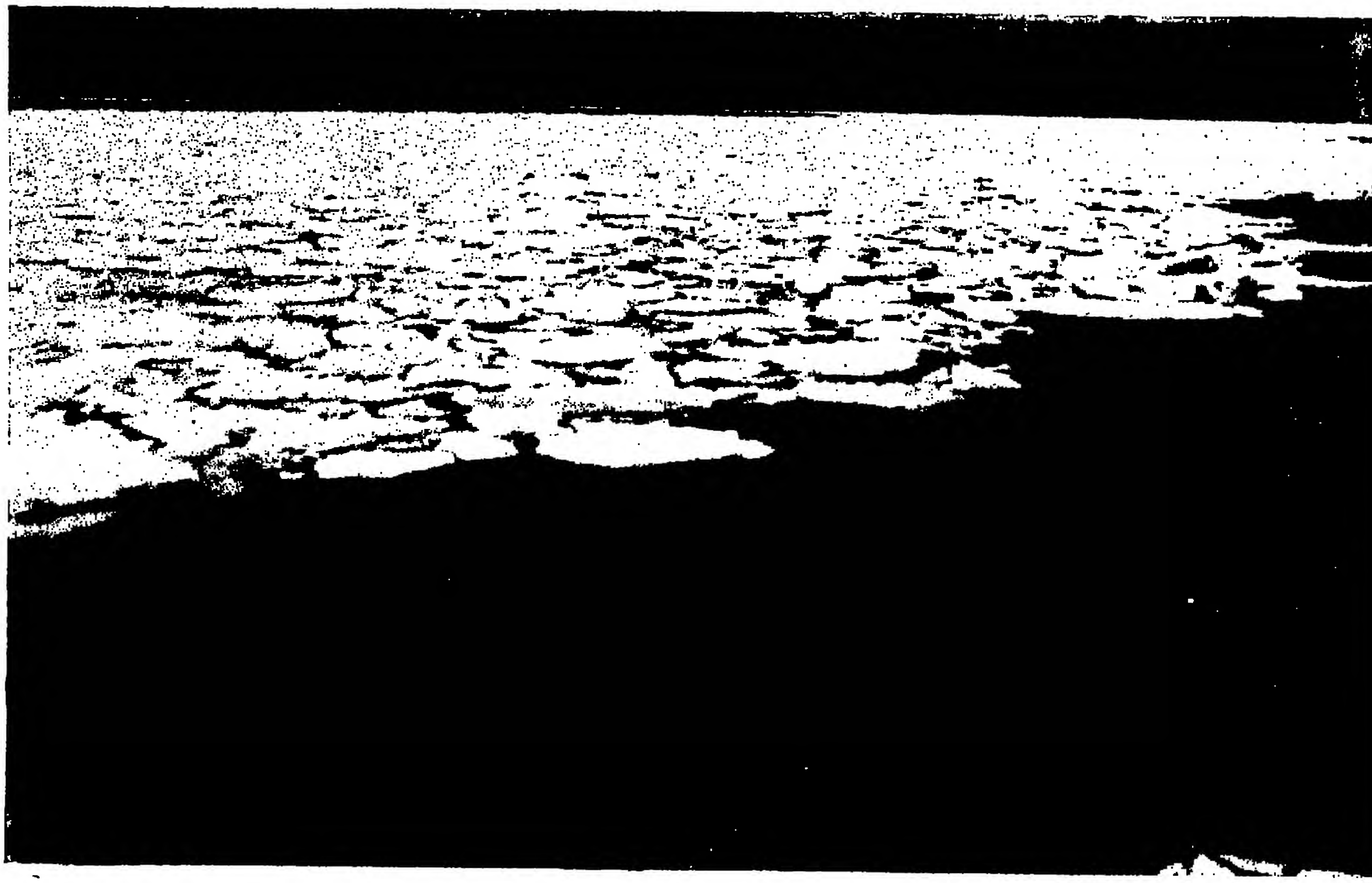
Page 393.

Photo by Priestley.

Plate CCLIII.—A Crack in Pack-Ice.

Photo by Ponting.

Page 393.



Page 393. Plate CCLIV.—A Lead in Pack-Ice. *Photo by Ponting.*

Page 393. Plate CCLV.—A Pool in Pack-Ice. *Photo by Ponting.*

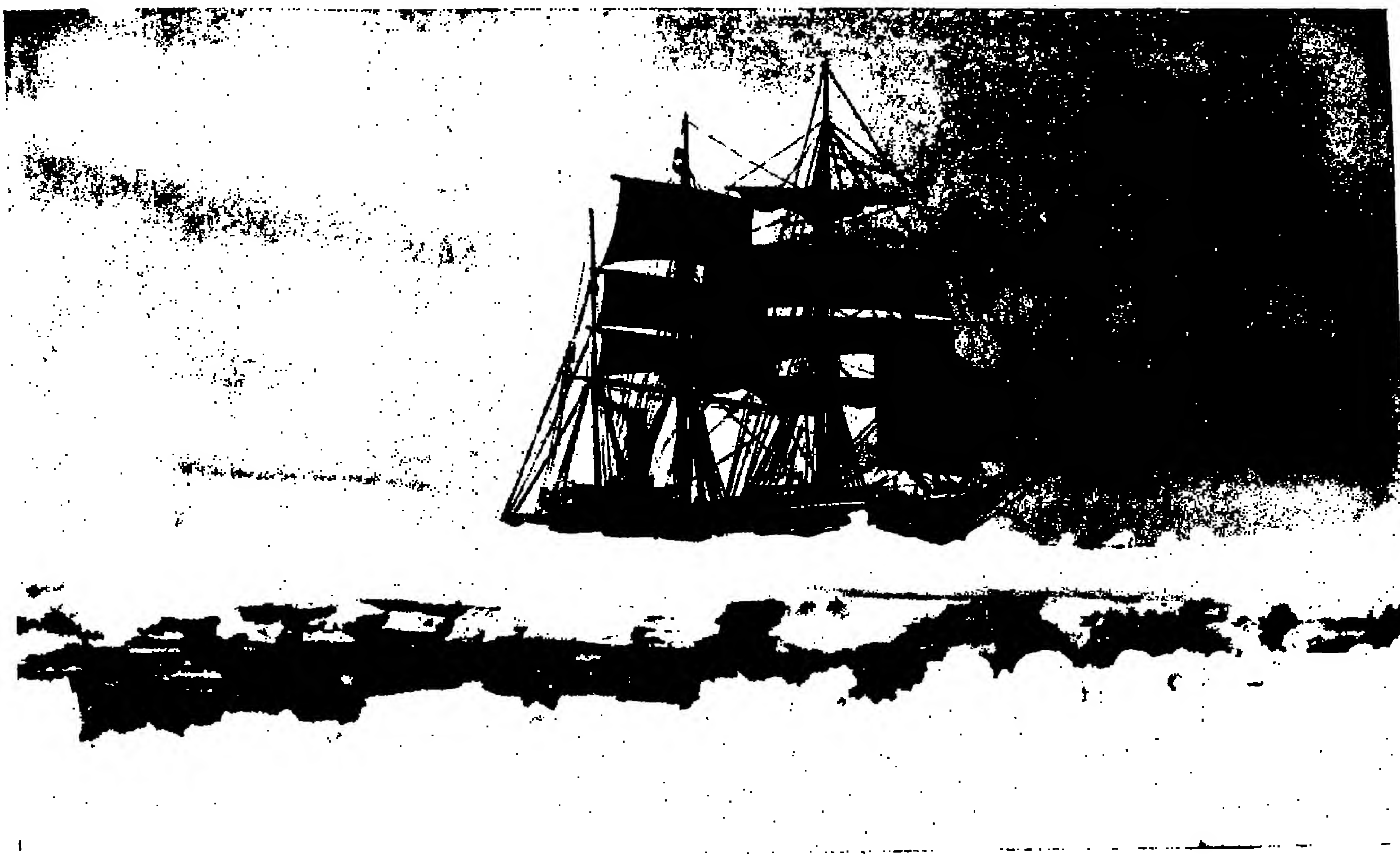


Plate CCLVI.—The "Terra Nova" beside a Hummocky-Floe.

Page 304. *Photo by Ponting.*

Plate CCLVII.—Close Pack.

Page 304. *Photo by Levick.*

Page 304.

Plate CCLVIII.—Open Pack.

Photo by Ponting.

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Plate CCLIX.—Drift-Ice.

Photo by Ponting.

Plate CCLX.—Brash-Ice.

Photo by Priestley.

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Plate CCLXI.—Brash-Ice between Floes.

Photo by Ponting.

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Plate CCLXII.—Small Growler.

Photo by Ponting.

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Plate CCLXIII.—Rotten-Ice.

Photo by Ponting.

Plate CCLXIV.—Small Hummocky-Floe.

Page 307.

Photo by Priestley.

Plate CCLXV.—Hummocky-Floe surrounded by Rafted Ice.

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Photo by Levick

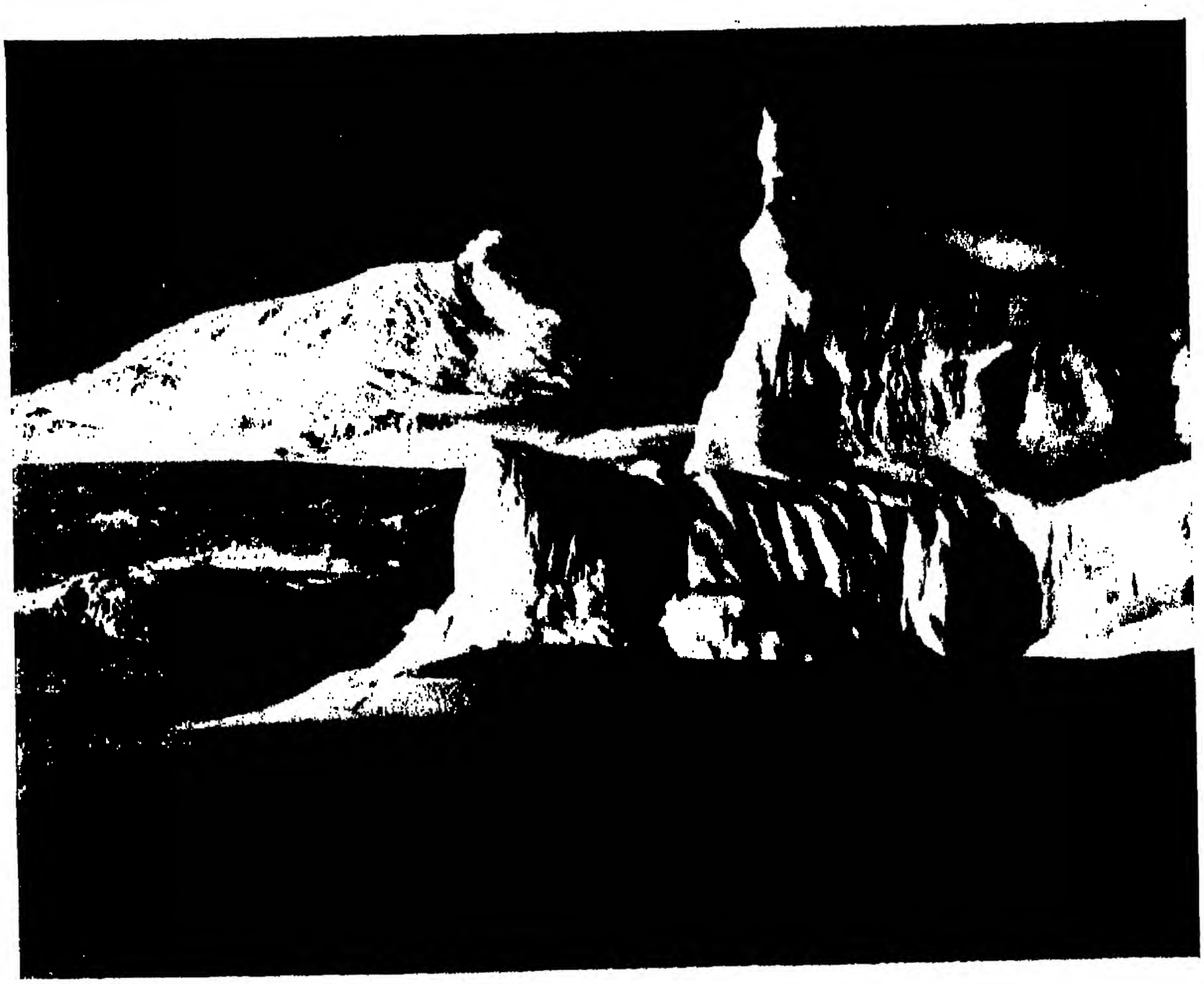

Plate CCLXVI.—Iceberg with coating of Sea-Spray.

Page 405.

Photo by Ponting.

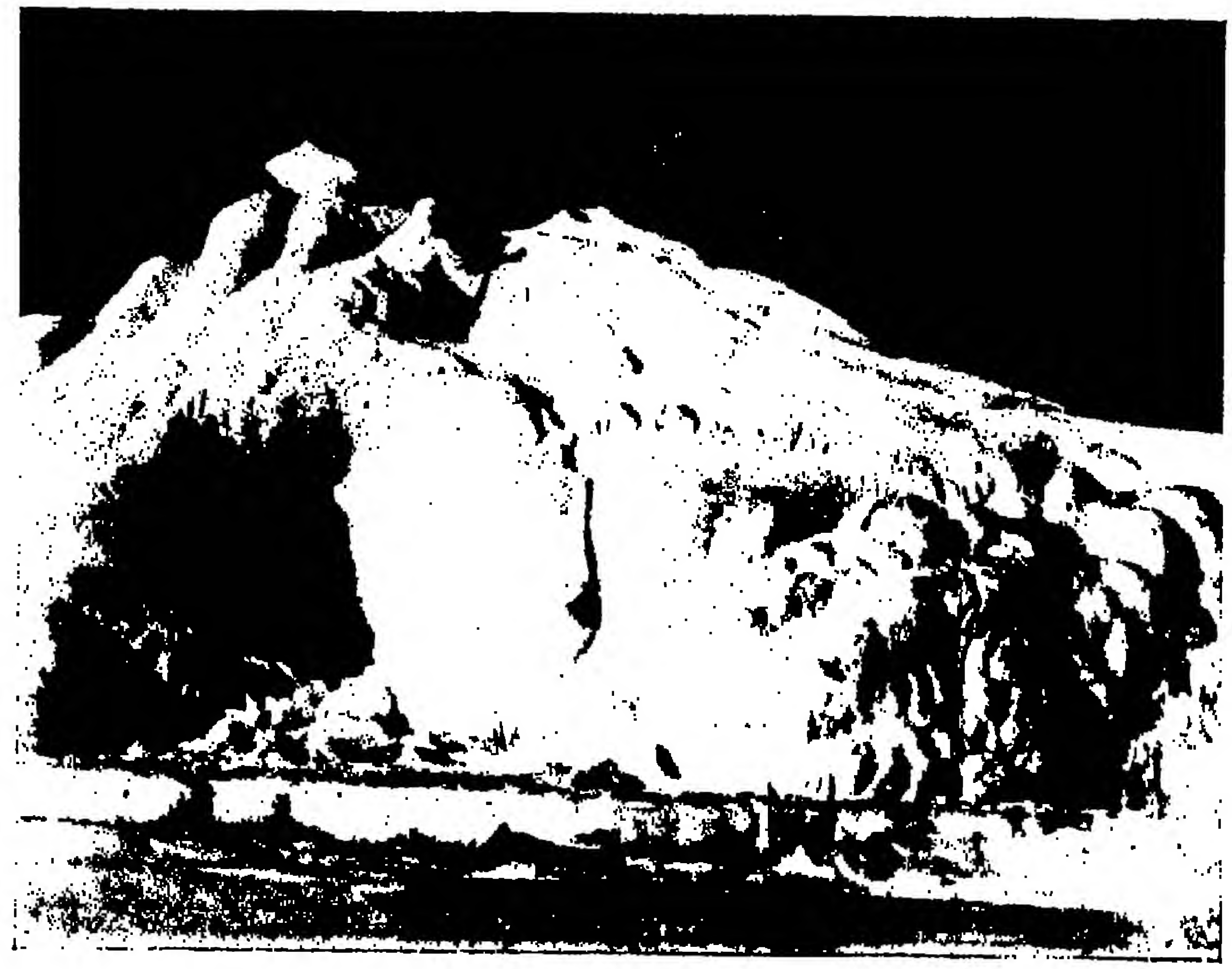

Plate CCLXVII.—Stranded Iceberg with Tidal Platform.

Page 405. *Photo by Levick.*

Plate CCLXVIII.—Crack formed in Iceberg due to temperature changes.

Page 405. *Photo by Priestley.*

Plate CCLXIX.—Crumbling of upper portion of Iceberg due to frost action.

Page 405. *Photo by Priestley.*

Plate CCLXX.—Calving of a fragment of a Glacier to form an Iceberg.

Page 407. *Photo by Ponting.*

Spur

Plate CCLXXI.—Iceberg showing submarine spur to the left.

Page 408. *Photo by Ponting.*

Page 408. Plate CCLXXII.—Showing undercutting of an Iceberg by sea water. *Telephoto by Ponting.*

Page 408. Plate CCLXXIII.—Iceberg showing undercutting by sea water. *Photo by Ponting.*

Plate CCLXXIV. Tabular Iceberg showing a combination of undercutting and overcutting by sea water.
Photo by Ponting.
Page 408.

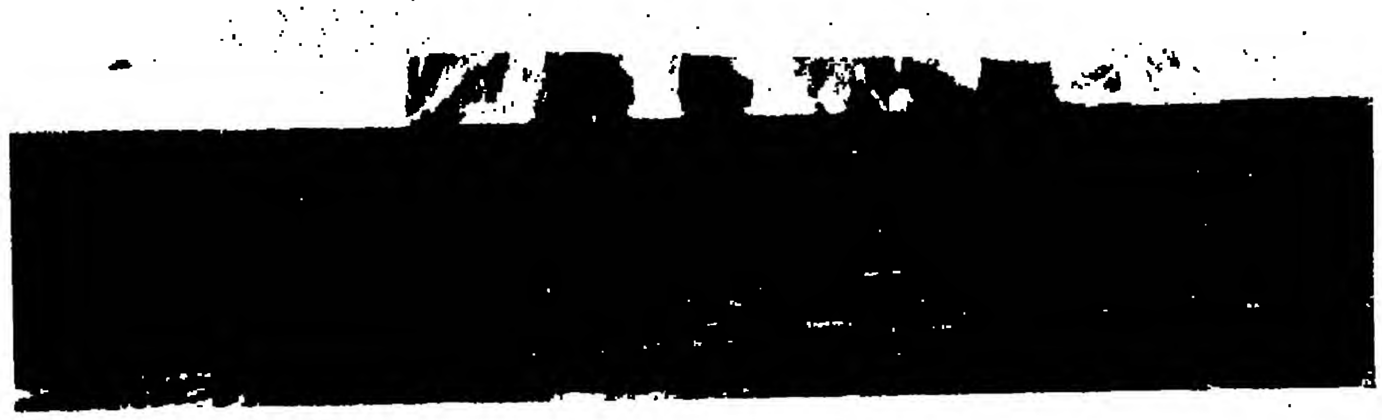

Plate CCLXXV.—Caves in Iceberg due to wave action.
Photo by Levick.
Page 400.

Page 400.
Plate CCLXXVI.—Caves in Iceberg due to wave action.

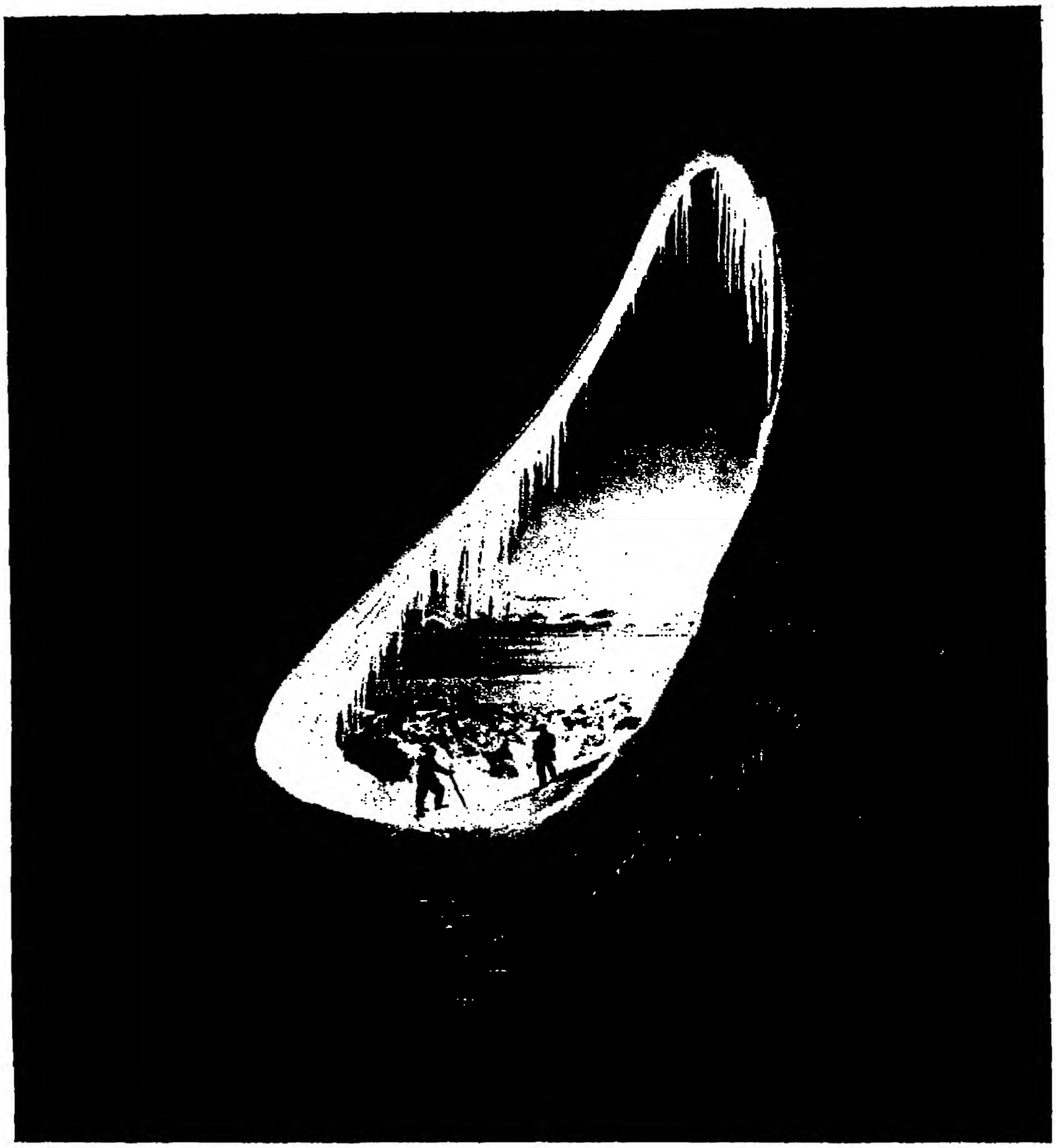

Plate CCLXXVII.—Cave in Iceberg due to displacement of top portion (left) of the berg on tilting through a large angle. (Note difference in texture of the two portions of the berg.)

Page 409. *Photo by Ponting.*

Plate CCLXXVIII.—Cubical Remnants standing up after collapse of portions of an Iceberg.

Page 410. *Photo by Priestley.*

Plate CCLXXIX.—The effect of jointing on the weathering of an Iceberg.
Page 410. *Photo by Levick.*

Plate CCLXXX.—Iceberg with smooth water-shaped contours.
Page 411. *Photo by Levick.*

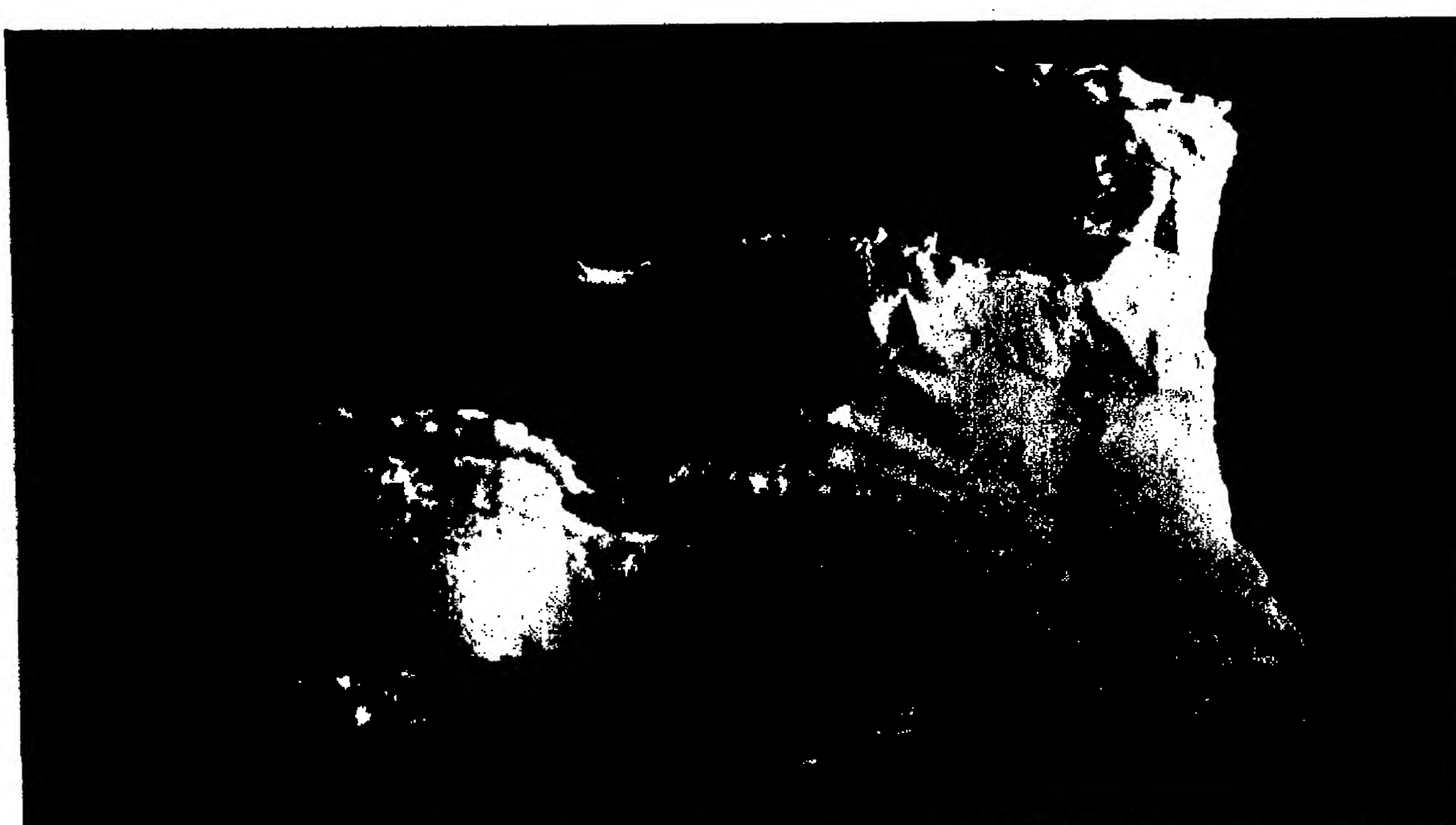

Plate CCLXXXI.—Water-worn Iceberg, illustrating method of formation of Swan-Ice. *Photo by Ponting.*
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Plate CCLXXXII.

Plate CCLXXXIII.

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Two photos of the same piece of Swan-Ice taken on successive days.

Photos by Priestley.

Page 413.

Plate CCLXXXIV.—Tabular Iceberg.

Photo by Ponting.

Plate CCLXXXV.—Glacier Iceberg.

Photo by Ponting.

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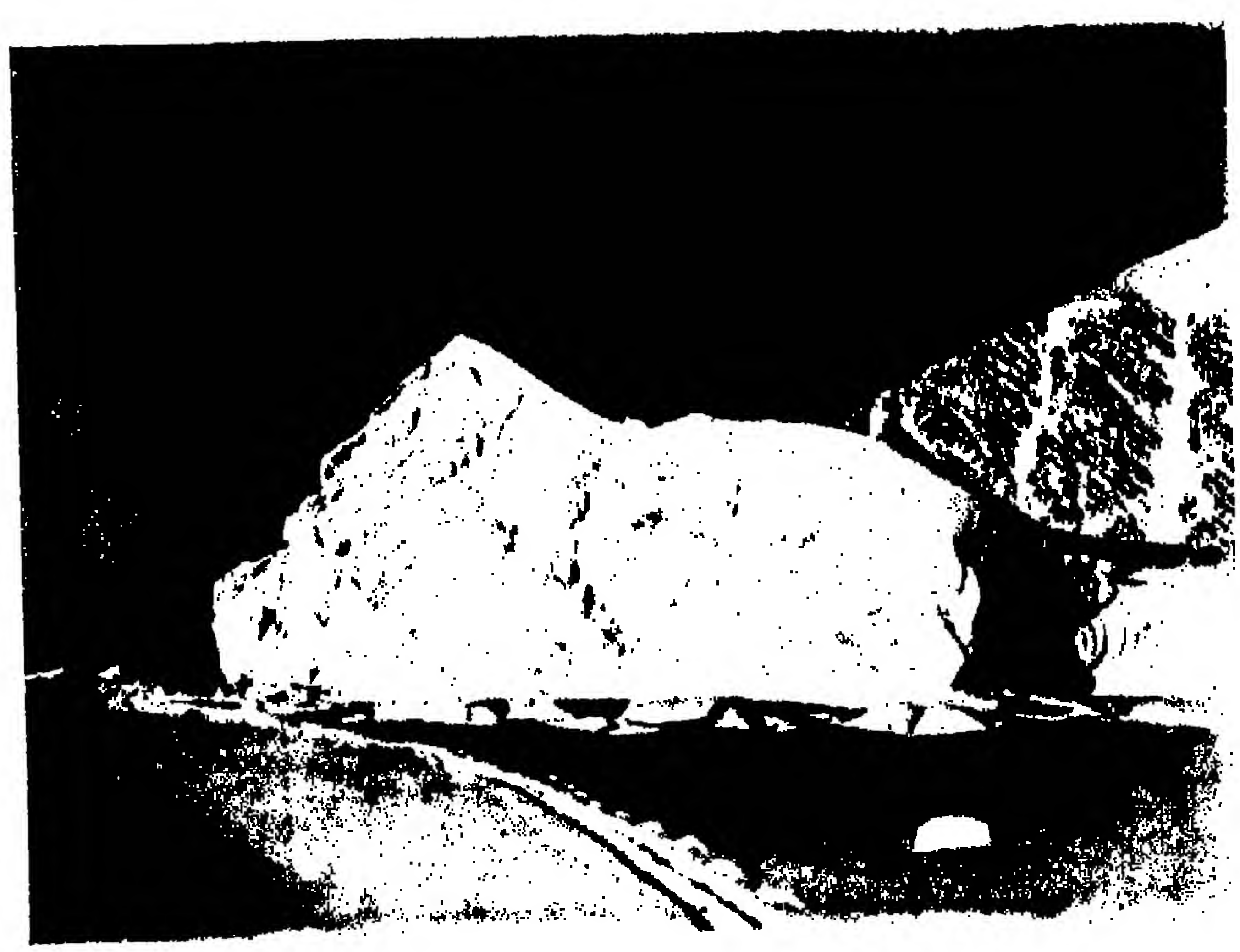

Plate CCLXXXVI.—Glacier Iceberg.

Photo by Levick.

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Plate CCLXXXVII.—Ice Island Iceberg.

Photo by Ponting.

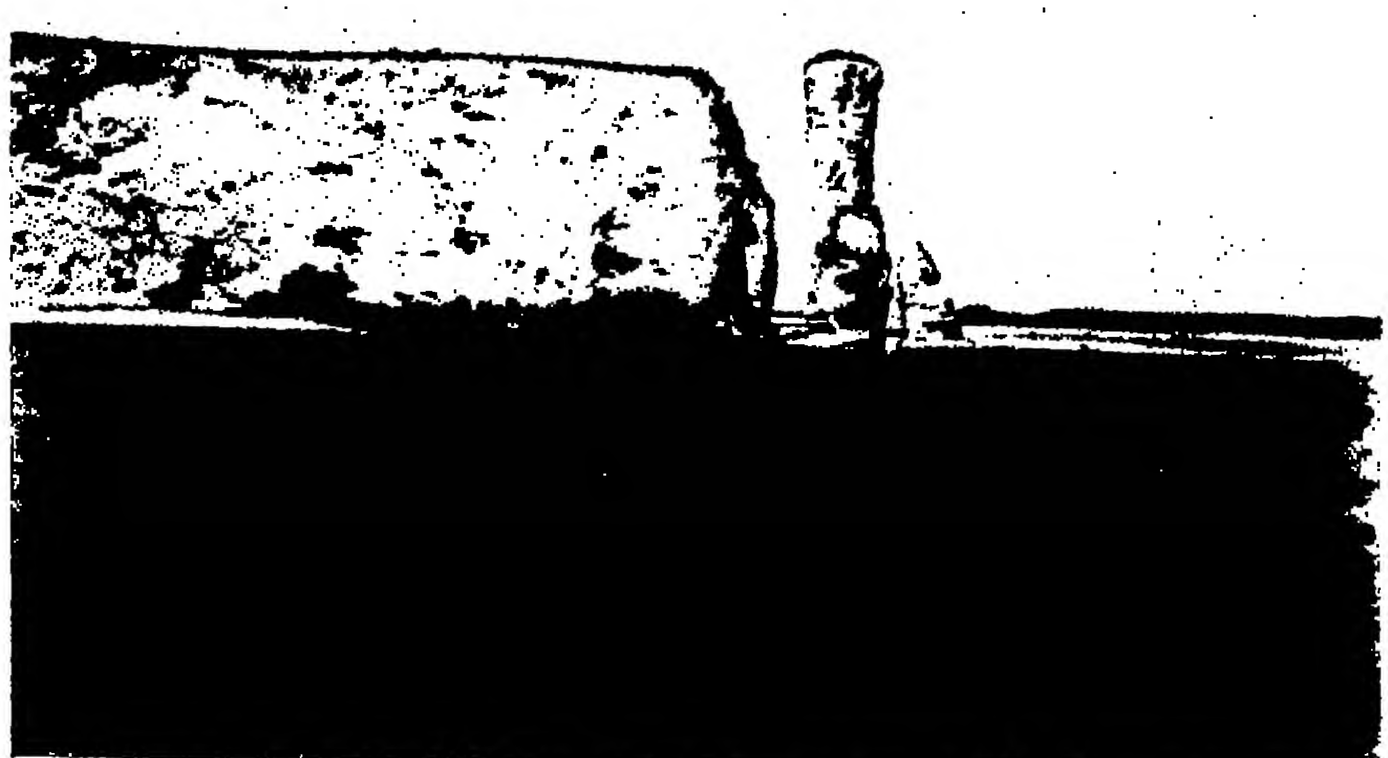

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Plate CCLXXXVIII.—Névé Berg.

Photo by Wright.

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Plate CCLXXXIX.—Weathered Icebergs.

Photo by Ponting.

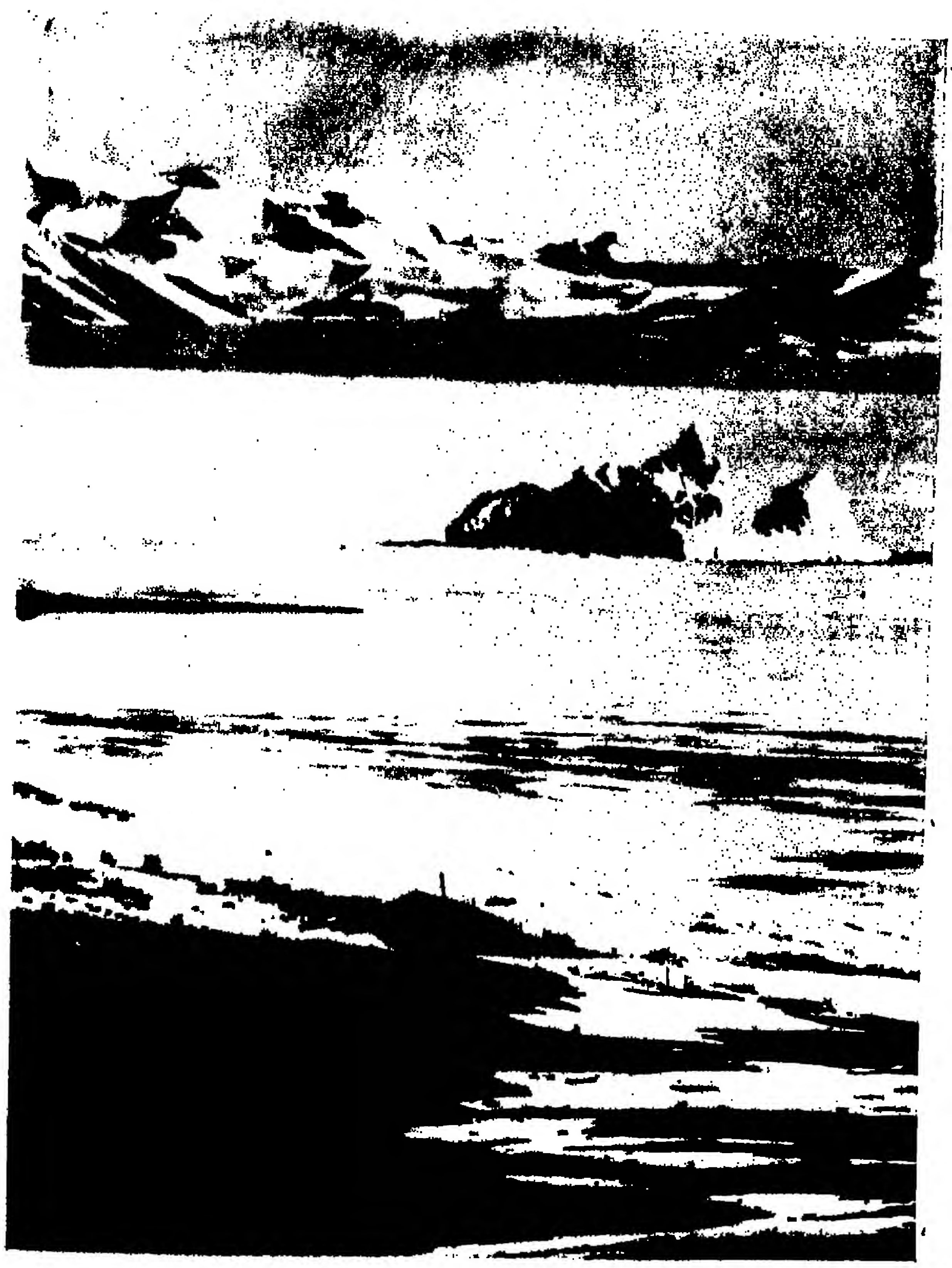

Plate CCXC.—Weathered Iceberg.

Page 416.

Photo by Ponting.

Plate CCXCI.—The result of an Iceberg charging the fa
a Glacier.

Page 417.

Photo by L